QJEGH

Case study *Quarterly Journal of Engineering Geology and Hydrogeology*

Published Online First https://doi.org/10.1144/qjegh2018-213

The potential use of mine water for a district heating scheme at Caerau, Upper Llynfi valley, South Wales, UK Q2

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Abstract: The feasibility of recovering heat energy from mine water contained within an abandoned coal mine in South Wales is assessed for a proposed district heating scheme. The study area is the village of Caerau, in the Upper Llynfi valley, Bridgend County Borough, South Wales, UK, comprising around 750 residential houses, a primary school and 17 commercial properties. This paper describes an archival geological and mining desk study focused on Caerau colliery, consideration of regional mine linkages, geographical information system (GIS) techniques used to create a 3D initial conceptual geological mine model of Caerau workings, permitting and licencing requirements, community engagement activities undertaken and the findings of a Q4 single exploratory borehole. The borehole intersected a void space in flooded mine workings around the horizon of the Six Foot seam at a depth of 224 m below ground level, as predicted by the conceptual mine model. The rest water level within the borehole lies at 92 m below ground level and the measured *in situ* temperature of the mine water at the base of the borehole was 20.3°C. An unexpectedly high and sustained geothermal gradient of *c.* 53°C km^{-1} was calculated from repeated measured temperature profiles.

This article is part of the Keeping lessons alive in engineering geology available at https://www.lyellcollection.org/cc/keeping-lessons-alive-in-engineering-geology

Received 19 December 2018; **revised** 16 September 2019; **accepted** 30 October 2019

Supplying secure, affordable and sustainable future energy whilst also reducing CO_2 emissions is one of the greatest challenges facing the world today. Heating and hot water supplied to UK buildings make up around 40% of our energy consumption and 20% of our greenhouse gas emissions (Committee on Climate Change 2016). In the future the demand for space cooling in buildings is expected to increase significantly. The UK National Grid has previously estimated the uptake of air conditioners in the domestic sector to be 18 million units by 2050, compared with less than one million in use today (National Grid 2018). It will be necessary to cut CO_2 emissions to almost zero by 2050 to achieve UK Government targets.

In 2016, Wales' gas consumption for heating was 22 045 GWh and it was estimated that around 23% (*c.* 291 000) of households in Wales were living in fuel poverty (Davies 2017; DBEIS 2018). Fuel poverty is defined as having to spend more than 10% of income (including housing benefit) on all household fuel use to maintain a satisfactory heating regime (Welsh Government 2010). Contributing factors for fuel poverty in Wales include 29% of properties being solid-wall constructed homes and 21% of properties being off the gas grid (National Assembly for Wales 2018).

Mine water could potentially provide a sustainable, low-enthalpy heating source to supplement the renewable energy mix in the UK, whilst also improving energy security (Bailey *et al.* 2016). It is a well-recognized fact that coal mines, after abandonment, slowly flood with groundwater. Exothermic geochemical reactions involving minerals and groundwater make the mine water warm in addition to the local geothermal gradient (Banks *et al.* 2004; Younger 2014; Farr *et al.* 2016). Thus, an abandoned mine potentially represents a thermal energy source in the form of accessible mine water.

Overview of heat recovery schemes from abandoned coal mines

Heat recovery projects from flooded mines have been in operation in both the USA and Europe since the 1980s (Jessop & Macdonald 1995; Banks *et al.* 2003; Watzlaf & Ackman 2006; Wieber & Pohl 2008; Hall *et al.* 2011; Verhoeven *et al.* 2014; Ramos *et al.* 2015; Farr *et al.* 2016). In Europe, operational systems exist in Germany, Poland, Norway, the Netherlands, Spain and the UK (Banks *et al.* 2004; Raymond & Therrien 2008; Hall *et al.* 2011; REMINING-Lowex 2012; Jardón *et al.* 2013; Preene & Younger 2014). District heating is supplied by a mine water scheme in the municipality of Heerlen, Netherlands, where a low-temperature district heating system has been in operation since October 2008 (Minewater Project 2013; Verhoeven *et al.* 2014). A similar scheme was successfully implemented in the city of Asturias, Spain, where a geothermal system used water stored in Barredo–Figaredo reservoir to supply heating and cooling to two buildings on the campus of the University of Oviedo and a hospital (Jardón *et al.* 2013). Q5

In the UK, heat recovery from abandoned coal mines was first piloted at Mossend, Scotland in 1992, followed by two permanent sites commissioned in 1999–2000 at Shettleston and Lumphinnans (Banks *et al.* 2009). The Coal Authority operate a demonstration system at Dawdon, County Durham (Bailey *et al.* 2013; Satterley *et al.* 2017), which was built to stimulate confidence in mine water heating schemes. Athresh *et al.* (2015), Burnside *et al.* (2016) and Banks *et al.* (2017) reported on a mine water pilot plant at the former

Markham Colliery, which is still in the process of flooding. A standing column heat pump arrangement has been used to heat office buildings through a single 20 kW commercial Danfoss heat pump. This scheme demonstrated another novel design and implementation of an open-loop ground source heat pump in an ochre-rich mine water environment (Athresh *et al.* (2016). Loredo *et al.* (2017) studied the importance of hydrochemical characterization of mine water for the optimal design of the geothermal installation, to understand the hydraulic behaviour of the water in the reservoir and prevent undesired effects such as clogging of pipe, heat exchangers and reinjection wells as a result of mineral precipitation. Banks *et al.* (2019) have also carried out heat extraction and recirculation tests within the shaft of abandoned hematite mine at Egremont, Cumbria.

Mine water heat recovery can be achieved using either open-loop or closed-loop systems (Ghomshei 2007; Banks *et al.* 2009; Hall *et al.* 2011; Preene & Younger 2014). Open-loop systems require water to be pumped from a borehole (or mine shaft) and circulated directly through the heat pump with the discharge water being returned via another borehole or shaft to the mine workings (open-loop system with reinjection of thermally spent water). In some examples, the thermally spent water is sent to a treatment system (open-loop system with disposal of thermally spent water; Banks *et al.* 2017). In open-loop systems with disposal of thermally spent water, the treated mine water is then sent to surface water courses. This type of scheme is suitable in locations where existing mine water treatment schemes are already operating. Open-loop systems with reinjection of thermally spent water return mine water via boreholes further down the hydrogeological gradient or to a disconnected part of the mine workings. The advantage of this approach is that it is a non-consumptive process and mine water does not require treatment and disposal. Open-loop systems with reinjection do require drilling and maintenance of abstraction and reinjection boreholes and careful design to avoid negative thermal 'feedback' if the connection between the abstraction and injection points is a direct shortcut. Closed-loop systems do not require the abstraction of mine water, as a liquid coolant is pumped to depth via a pipe network within a borehole to capture heat energy. The coolant is never in contact with the mine water and thus the closed-loop configuration is suitable where chemical contamination is an issue, or where flooded workings cannot be intercepted.

To support the uptake of local renewable heat sources in Wales, the SEREN project at Cardiff University, funded by the European Regional Development Fund, installed a local heat scheme by coupling ground source heat pump (GSHP) technology and flooded mine workings in 2013. The site is located at Crynant village in the Dulais valley, South Wales (grid reference [279340, 204290]; IEA Geothermal 2013). An open-loop heat pump scheme utilizes the mine water energy source to provide 40 kW of heating and hot water to a large farmhouse and adjoining office buildings. The scheme comprises two 64 m deep boreholes, one an abstraction borehole equipped with a borehole pump to abstract water at a constant 11.5°C and the second a discharge borehole, located 60 m south of the abstraction borehole, to return the thermally spent water to avoid a thermal short circuit.

South Wales' coalfield mine water temperatures are known to be variable, and it is estimated that 42 MW of heat could potentially be recovered from mine water based on the combined discharge rate of 2025 $l\ s^{-1}$ (Coal Authority data 1998–2014) from the 62 post-closure mining sites currently monitored by the Coal Authority within the coalfield (Farr *et al.* 2016). The nearest Coal Authority monitoring point is *c.* 5 miles away from the Caerau study area.

Bridgend County Borough Council (BCBC) has been at the forefront of the development of decentralized energy in Wales, having been successfully selected as one of three demonstrator local authorities for the smart system heating (SSH) programme. The northern part of BCBC is a region of extensive historical coal mining within the central coalfield (Cooke 2018; Coal Authority 2019). To assess the suitability of the abandoned coal mines to support a district mine water heat recovery network a detailed geotechnical, site-specific, feasibility investigation was undertaken. This paper presents a geological and mining desk study, initial 3D conceptual ground mine model (ICM), including an accurate geospatial distribution of mapped historical mine workings. Surface geographical information system (GIS) mapping is combined with the ICM to identify the precise location to drill an exploration borehole which targets an underground roadway.

Geographical and geological setting

Caerau is situated in the Upper Llynfi valley, which lies at the centre of the South Wales coalfield (Brabham 2009; Fig. 1). The coalfield extends 87 km east–west and 30 km north–south and comprises Westphalian strata of the Carboniferous, historically known as the Coal Measures group. The rocks comprise alternating sequences of sandstones, mudstones and siltstones, with numerous individual coal seams underlain by a seatearth (clay), which are typically folded and faulted by the Variscan orogeny (Howells 2007). The central coalfield topography consists of an upland plateau, deeply incised during the Quaternary period by valley glaciers (Howells 2007). The last of the valley glaciers melted around 20 000 years ago and the valleys are now occupied by Holocene rivers eroding through the strata (Brabham 2009).

The South Wales coalfield was a world-famous, highly productive mining region with a complex 250 year history. The coalfield is renowned for its enigmatic 3D spatial distribution of coal grades (rank) from bituminous to steam and to high-grade anthracite coals (Gayer *et al.* 1991; White 1991). Over 3 billion tons of coal have been mined in South Wales since colliery output statistics began in 1850 (Brabham 2005). No definitive historical and geospatial database of coal mines exists for the South Wales coalfield, but independent studies indicate that there were between 2000 and 4000 historical mining operations over a large range of scales (Preston 2010; Cooke 2018). In 2019, only one underground coal mine still operates in South Wales at Aberpergwm in the Neath valley (grid reference [286500, 205950]). When deep coal mines were operational, they were protected from flooding by continual groundwater pumping. After abandonment, the pumps were turned off and the mines gradually flooded.

Historical Llynfi valley regional mining

Commercial mining in the Llynfi valley is first recorded in 1771 (Lewis 2006). A preliminary regional mining desk study focused at Caerau colliery has been undertaken by Sahid (2016). Statutory mining abandonment plans exist in Coal Authority archives dated from 1872 onwards and more inconsistently back to around 1840, so early shallow mining in the Llynfi valley predates these records. Coal mine abandonment plans in South Wales are a mosaic of individual coal seam maps, which may or may not be accurately geo-referenced in two or three dimensions depending on their age. A complication in South Wales is that originally local names were given to individual coal seams. Coal seam names were therefore not consistent between collieries until a standardized National Coal Board (NCB) nomenclature was finally employed and correlations were made (Adams 1967). A detailed study of a large colliery is commonly geologically complex in three dimensions. Underground mining expanded over decades radially away from the main shafts, extracting coal from multiple seams, constrained by private company mineral licence areas and geological faults. Over an operational period of 50–100 years, deeper seam horizons were

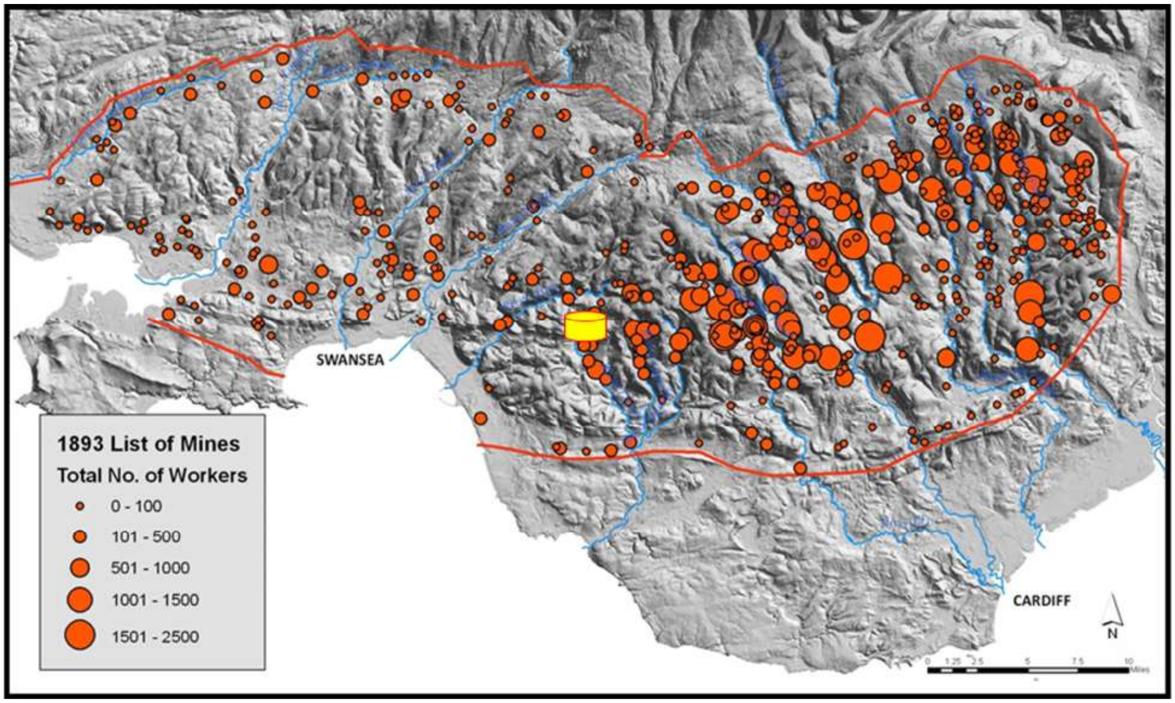

Fig. 1. Topographic map of the South Wales coalfield (outlined in red) showing the major rivers (blue), significant coal mines and their relative workforce in 1893. Caerau colliery is highlighted as a yellow cylinder (adapted from Preston 2010). Copyright LIDAR data topography Welsh Assembly Government LLE geo-data portal. Q23

exploited as groundwater and ventilation pumping technology improved.

The Llynfi valley contained up to 60 coal mines over its history, plus numerous uncharted small mining operations (Lewis 2001; Brabham 2009; Lawrence 2017; Cooke 2018). Figure 2 shows that the Upper Llynfi and adjacent areas contain extensive areas of coal workings. The main town and regional centre of the Llynfi valley is Maesteg, which is historically associated with late 18th century ironstone outcrop and adit mining for the local ironworks (Richards 1962; Ince 1993).

Although a colliery was originally an autonomous mining operation, many of the individual private company coal mines in South Wales became (owing to amalgamations and subsequent NCB nationalization) interlinked underground and between topographical valleys. Adjacent collieries mined the same local sequence of coal seams, broken up into mining blocks by fault structures (Woodland & Evans 1963). By 1935, four large interconnected mines, Caerau, Coegnant, Maesteg Deep and St John's, shared the mining take of the Upper Llynfi, which continued into the NCB period. The southern extent of mining in the Llynfi valley is bounded by the Moel Gilau fault and a complex geological structure known as the Jubilee Slide (Woodland & Evans 1963; Brabham 2009). The last operational NCB coal mine in the Llynfi valley was St John's, Maesteg, which closed in November 1985.

Coal Authority mine plans show that Caerau colliery was connected by direct roadways and/or interconnected seam horizons to Dyffryn Rhondda (Afan valley) to the NW and Coegnant (Llynfi valley) to the south. Coegnant colliery was connected southwards to two other Llynfi valley mines, Maesteg Deep and St John's. To the east, Caerau was connected to International (Garw valley), which was connected to Garw/Ffalddau (Garw valley). Connections continue to Wyndam and Western (Ogmore Vale) and finally to Eastern colliery, located on the mountainside above Gelli in the Rhondda Fawr valley. This potential subsurface interconnected zone of mine workings in the central coalfield is 7.5 miles (13 km) west to east and covers an area of *c.* 26 miles^2 (68 km^2) in extent (Fig. 3).

The local geological stratigraphy at Caerau

Caerau colliery operated over 78 years, opening in 1899 and closing in 1977. Caerau was a medium-sized colliery employing 1800 workers at its peak of production around 1914 (Cooke 2018). Caerau colliery initially accessed the subsurface by three vertical shafts: South, North and No. 3 at depths of 320, 324 and 157 m below ground level (bgl). Mining plans indicate that only the North shaft was later extended to a depth of 397 m to access deeper seam horizons. Historical mining records, BGS maps and reports indicate that there are 20 potential and 13 known worked coal seam horizons at Caerau. The standard NCB name, original historical name and typical Upper Llynfi valley thickness of these seams is listed in Table 1. Figure 4 shows a geological log section for the Caerau colliery area in relation to valley topography compiled from BGS maps and reports (Woodland & Evans 1963). At Caerau, the geology dips 10–13° to the north and is cut by NW–SE-trending normal faulting, typical of the central coalfield (Brabham 2009).

Caerau colliery 3D conceptual geological and coal mining model

To understand the post mine closure changes in land surface topography, modern and historical (1947) landscape models were created by geo-referencing air photography (Fig. 5). To create a subsurface mine model, digital scans of 36 Coal Authority mine abandonment plans of Caerau and the adjacent Coegnant colliery were obtained for this study. A western mined area was confirmed beneath Caerau village, making the mine water energy project feasible (Fig. 6). Mine plans were geo-referenced in 3D space, combined as seam mosaics and then digitized in relation to surface

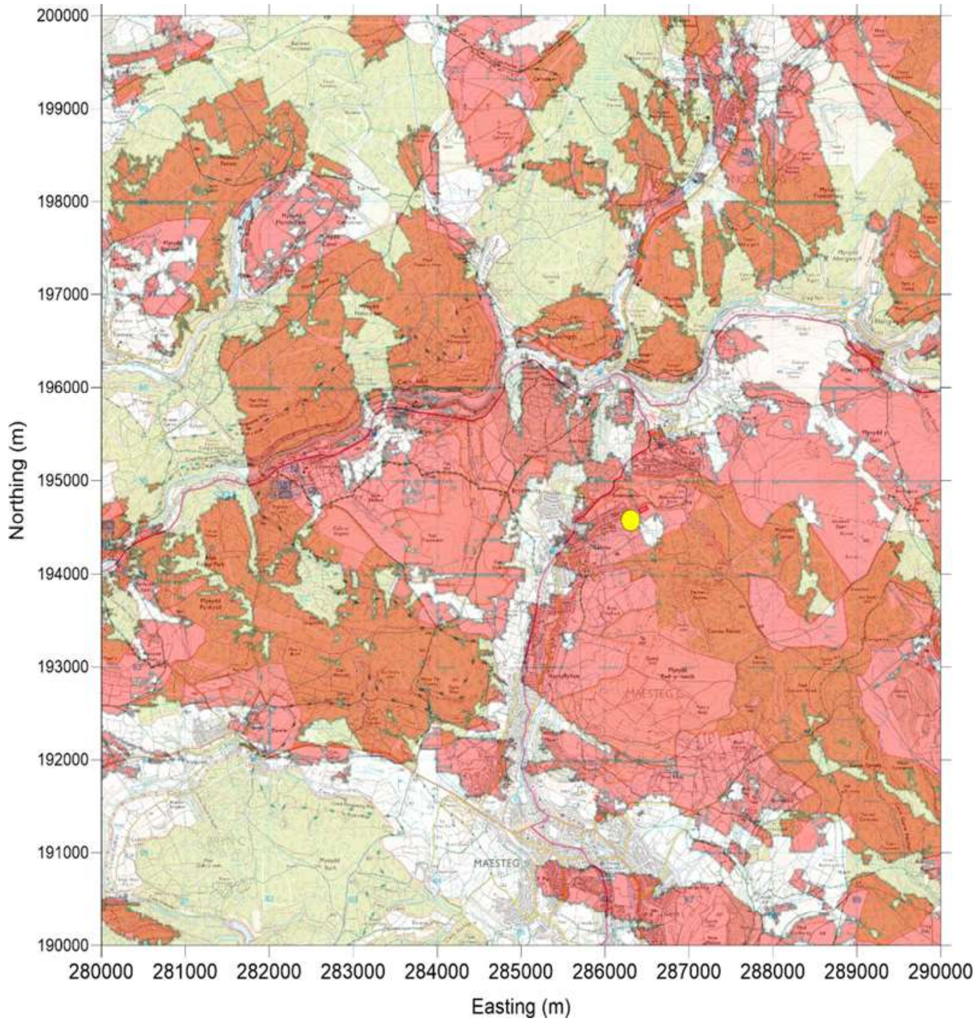

Fig. 2. Total aerial extent of known coal mined areas (red) in the Upper Llynfi valley and adjacent areas. Caerau colliery location is shown as a yellow circle. Reproduced with the permission of © The Coal Authority. All rights reserved.

topography to create a mine model illustrating the shafts, roadways (Fig. 7) and extent of individual coal seam exploitation beneath Caerau (Fig. 8). Caerau colliery accessed shallow seams (Victoria to Caedavid; Fig. 4) via the No. 3 shaft. The Six Foot and deeper seams were accessed via the South and North shafts, with horizontal roadways extending west and east out from pit bottom and underground inclined roadway linkages between mining horizons.

From close inspection of the historical mine plans, it is interpreted that the manual longwall mining method was mainly employed in the deeper seams (Statham 2004). By employing longwall mining methods coal is totally removed in the form of panels. Dates of mining operations and pumping rates are also annotated on the mine plans. The boundary of mining in the Six Foot seam appears to have been reached in the western area between 1915 and 1921 and the final extent of mining of this seam horizon occurred between 1944 and 1946. After mining ceased, it is expected that only major roadways and shafts were left as void spaces, and the rest of the longwall mined area becomes collapsed ground (goaf) after the removal of the roof supports. The roadway tunnels and the collapsed goaf areas will increase strata permeability compared with unmined ground. The Six Foot workings are divided into two distinct mining areas (west and east) by a NW–SE-trending fault with a downthrow to the east. The Caerau colliery shafts lie in the eastern mined area and hard heading tunnels were driven westwards from the pit bottom across the fault to access the western mining area.

Groundwater rebound and historical mine pumping data

Robins *et al.* (2008) carried out a regional study of groundwater flow for the South Wales coalfield, which predicts that groundwater rebound is largely complete for the abandoned coalfield. Harris (2017) carried out a review of historical NCB groundwater pumping data collected at collieries in the coalfield. Historical pumping information indicates that groundwater was pumped from Caerau colliery at the North shaft at 5.2 l s^{-1} in the Six Foot seam and at 4 l s^{-1} from the Nine Foot horizon. The interconnected Duffryn Rhondda colliery pumped at a rate of over 1.7 million litres a day (19.7 l s^{-1}). Despite the absence of any nearby monitoring boreholes from which to measure mine water rebound, we consider that these historical pumping rates indicate that it is highly likely that the mine workings at Caerau colliery are now significantly flooded over 42 years since mine abandonment.

Identifying drilling location for test borehole

The mining model was used to identify potential locations for an exploratory borehole, targeting two extensively worked coal seams beneath Caerau village: the Six Foot and Nine Foot horizons (Fig. 6). The first option was to directly access the Caerau colliery shafts; however, the shafts had been backfilled and capped and the area landscaped over by the Coal Authority in 2001. The land

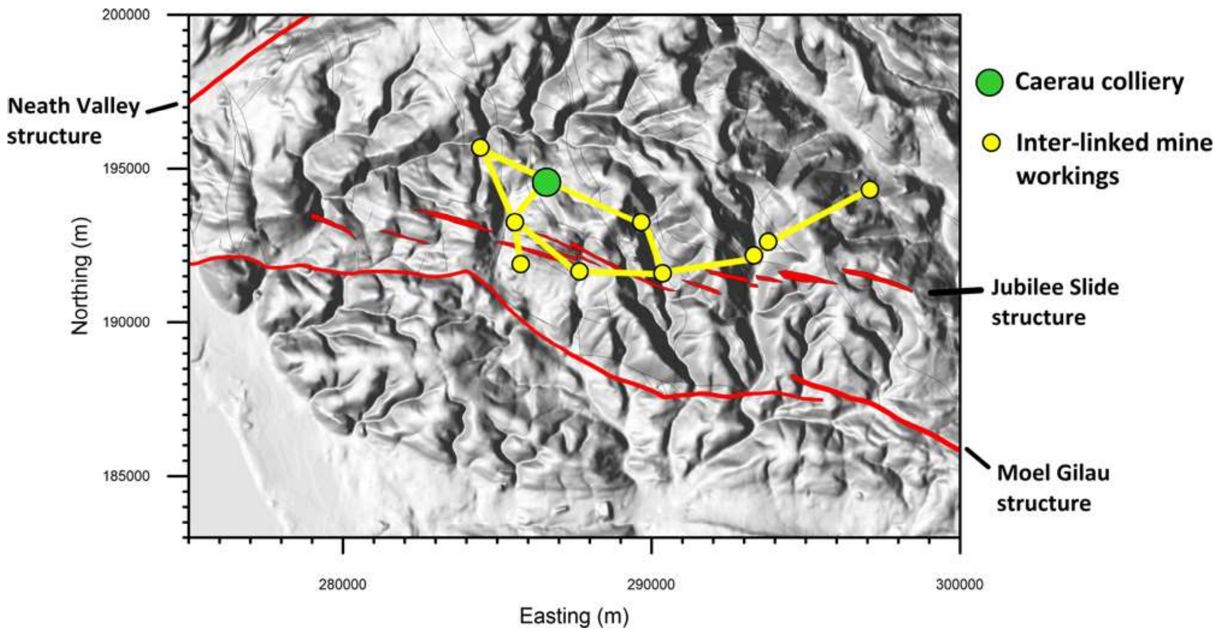

Fig. 3. Interlinking of mines in the central coalfield: Dyffryn Rhondda–Caerau (green)–Coegnant–Maesteg Deep–St John's–Ffaldau–Garw–Wyndam–Western–Eastern collieries and bounding geological structures. Copyright LIDAR data topography Welsh Assembly Government LLE geo-data portal.

restoration scheme has resulted in an unknown thickness of landscaped colliery spoil at proposed locations. Drilling through tip material would be expensive and high risk, and this option was ruled out as permission was not granted for drilling on the reprofiled tip areas (Fig. 5).

The second option was to drill a borehole directly targeted at the main access roadways, running horizontally from pit bottom within the cylinder of unmined geology left around the shafts to avoid destabilization (Fig. 6). Potential surface drilling locations were again located on reprofiled tip material, so this option was also discounted.

The third option was to identify an accessible drill site located vertically above an underground roadway at the Six Foot horizon. A planning constraint was that a drill location had to be greater than 50 m away from housing and not close to the riverbank, so buffer zones were incorporated into the GIS model. Two potential drilling locations on BCBC land were identified 50 m apart, which met all the above criteria. If drilling encountered an unworked coal pillar in the Six Foot seam, there was also the option to drill on to a deeper target in the Nine Foot horizon vertically below.

Table 1. *Stratigraphical sequence of coal and ironstone horizons in Caerau area, with standardized NCB names, historical local names and approximate seam thicknesses*

NCB standard seam name	Historical seam name and indicative thickness
Pentre Rider	Victoria (0.9 m thick)
Lower blackband ironstone	Potential ironstone mining horizon
Upper Yard Seam	No. 8 (1.9 m thick)
Lower Pentre	Two and a Half seam (0.7 m thick)
Caedefaid seam	(0.9 m thick)
Two foot nine seam	
Upper four foot seam	
Lower four foot seam	(up to 2.4 m thick)
Upper Six foot seam	(1.0 m thick)
Lower Six foot seam	
Caerau seam	Seven foot seam (0.7 m thick)
Red vein	(1.2 m thick)
Upper Nine foot seam	Harvey (1.5 m thick)
Lower Nine foot seam	Upper New (1.3 m thick)
Bute seam	Lower New (1.2 thick)
Yard	No. 8 (0.7–1.0 m thick)
Seven Foot	(2.1 m–4.5 m thick)
Five foot	
Gellideg	
Garw	

Environmental permits, exemptions and licences

It was predicted that drilling would encounter water-filled mine workings at depth. All potential risks must be considered; there are two scenarios: (1) the workings are not flooded but may contain methane gas, which could potentially find a pathway up the borehole and may result in an explosion at the drilling rig; (2) mine water within the workings is under artesian pressure, and could migrate up the borehole to create an artesian well at surface and cause local flooding.

Prior to drilling, multiple licences and permits were required from various Government Agencies and landowners. A 'mine water heat recovery access agreement' was required from the Coal Authority for the purpose of drilling and extracting heat from mine water. Information is required on the vicinity of housing, drilling depth of proposed boreholes into target horizons, potential for spontaneous combustion, gas, water or other hazards, and all engineering specifications including sealing off boreholes with grouted-in casing.

Natural Resources Wales (NRW), the environmental regulator for Wales, required consents and exemptions. First, a 'consent to investigate a groundwater source' is required under Section 32 of the Water Resources Act 1991. This involves undertaking a water features survey in a 1 km radius around the drilling location to identify water monitoring points or abstractions that could be negatively affected. Second, a 'permit to discharge' was required to return any extracted mine water back into the same mine workings.

Although the potential drilling sites were identified on BCBC-owned land, planning consent had to be obtained from the local authority. A 1 month on-site temporary drilling licence for

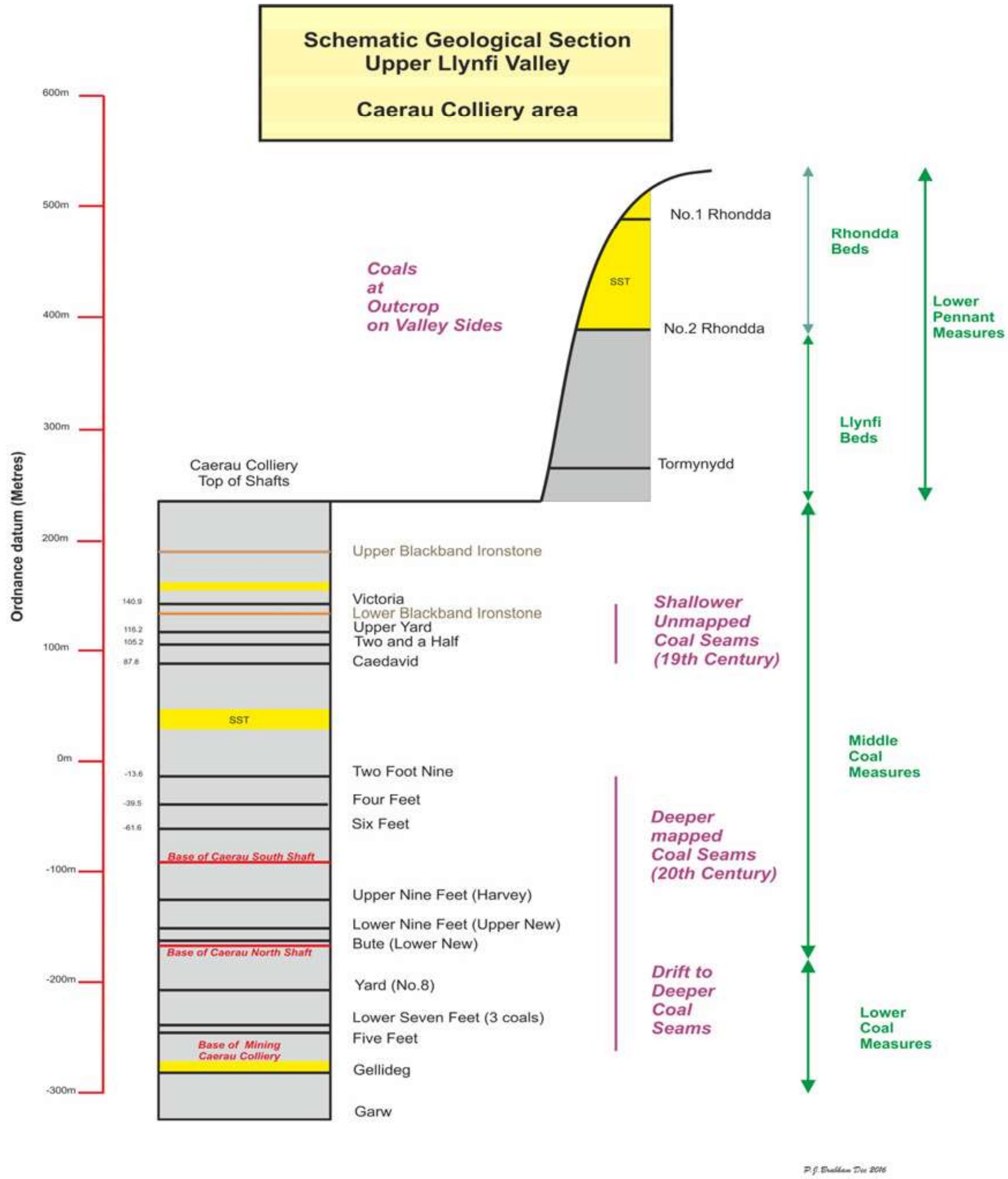

Fig. 4. Coal seam horizons in Caerau study area, compiled using Caerau colliery shaft logs and projected surface outcrops, using standardized NCB seam names and historical seam names in parentheses (Woodland & Evans 1963). Copyright BGS 1:10000 scale mapping interpreted by P. Brabham.

exploration was obtained, but only under condition of an operational window of 9 a.m. to 5 p.m. during weekdays only.

Through liaison between the project and the Health and Safety Executive (HSE) it was agreed that drilling would deploy sacrificial steel casing, solidly grouted into rockhead to block off any potential gas or artesian water migration pathways to surface. Drilling would incorporate a Washington control valve blow-out preventer that could be activated in the event of encountering artesian water or methane gas, triggered by on-site monitoring and alarm systems.

Caerau is located within an exploration block that is licenced for oil and gas exploration by the Welsh Government by a Petroleum Exploration and Development Licence (PEDL). At present there is a moratorium on any onshore methane exploration in Wales. Meetings took place with the PEDL licence holder in advance of drilling, over the legal ownership of any methane gas reserves that may be encountered.

Community engagement activities

The future success of any community heat from a mine water project relies on a strong and non-confrontational relationship with the local community throughout the project's lifespan. Given the current high-profile environmental resistance by local communities in the UK to fracking, it is essential that the community was aware that a mine water heat exploration project is not a fracking project. Planned drilling would take place within a compound in the heart of Caerau village over 1 month, so would be highly visible (Fig. 9). A BCBC–Cardiff University community engagement team commenced with a pre-engagement phase where key stakeholders, local enablers, landowners and community groups were identified and a public engagement programme was designed. In the pre-drilling phase, activities included attendance at advertised public events. Targeted leaflet or letter drops, feedback forms and social media outreach were all developed throughout the project timescale. Fact sheets

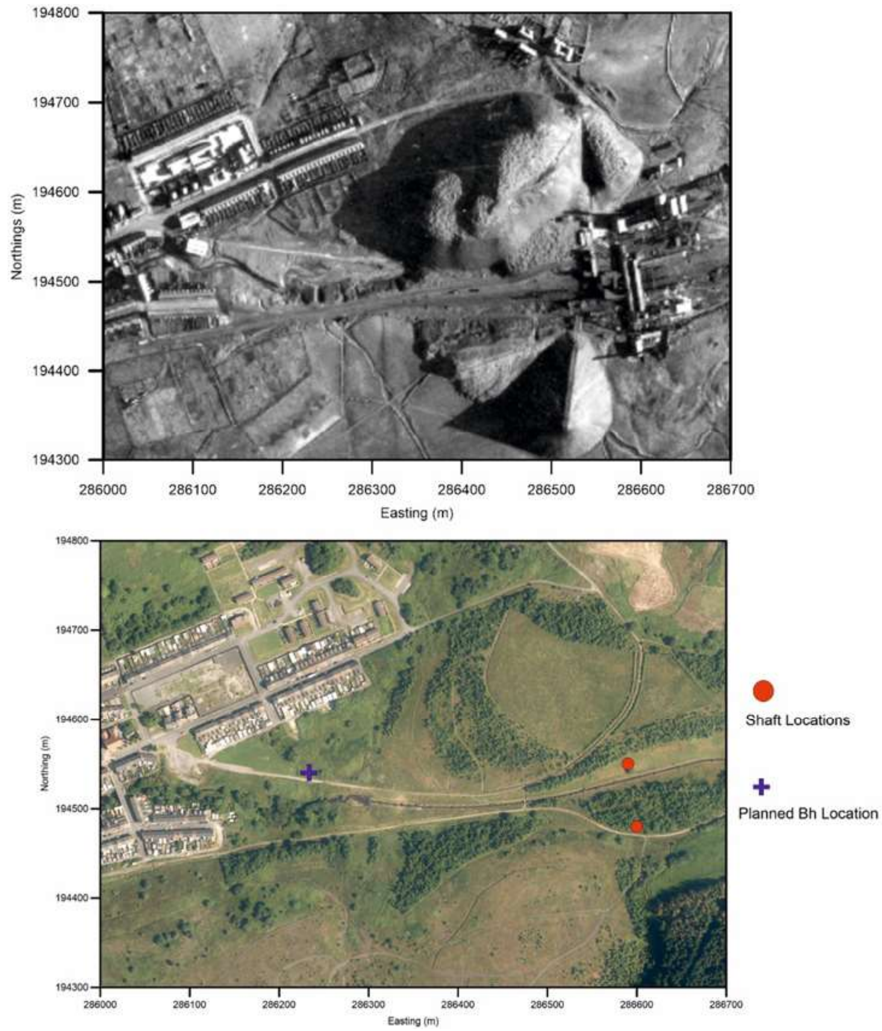

Fig. 5. Comparison of historical operational mining landscape (1947) with a modern air photograph (2016) showing the major landscaping of the Caerau colliery site, which was completed in 2001. The borehole location is also indicated. Copyright Welsh Assembly Government, Edina Digimap, Crown Copyright.

gave Caerau residents information regarding the project's aims and objectives and alerting residents to the planned drilling activities. Individual householders' concerns about drilling-induced mining subsidence, earthquakes or disturbance to wildlife were also addressed and science, technology, engineering and mathematics (STEM) geo-energy educational sessions were developed with local schools. During the drilling, on-site personnel were present to engage with residents. Post drilling phase, residents were updated on the findings of the project, in anticipation of any subsequent project phases. To maintain trust, it is critical that all external communication is clear, accurate and factual and that, where possible, the project is delivered precisely within the boundaries of what has been communicated. Any unplanned deviations from the programme were also communicated rapidly and transparently via social media updates. Generally, survey feedback showed that the residents of Caerau were positive to the idea of utilizing the historical flooded mine workings beneath their village as a future energy resource.

Results of exploration drilling

On-site preparation began on 27 September 2017; steel casing was installed to a depth of 13 m bgl into rockhead and grouted up with cement. Exploration drilling then commenced at a 4 inch (10.16 cm) diameter specification using an air flush hammer bit technique. A sandstone aquifer horizon was encountered at 106 m and the drilling technique was then changed to water circulation using a rotary coring bit. No shallow unmapped mine workings were encountered.

Drilling encountered a void space at a depth of 224–225 m bgl. This depth was within the survey margin error for the predicted depth of the workings at the Six Foot coal seam horizon. Drilling was terminated at 234 m bgl in solid geology and the borehole headworks were completed using a solid plastic borehole liner with a slotted section at the base (Fig. 10). Because of planning permission time constraints and working with fixed financial drilling and site restoration budget costs, a second exploration borehole has not been drilled to date. The borehole and Caerau colliery shaft logs correlated well, taking into consideration surface topography and a mapped fault offset between the locations (Fig. 10).

Mine water temperature and the local geothermal gradient

Recent monitoring of geothermal gradients in the South Wales Coalfield displays an inconsistent pattern (Farr *et al.* 2016). Following completion of the exploratory borehole, downhole temperature measurements were made using a portable Solint™ temperature, level and conductivity dipper. Four temperature profiles were measured over 3 months between 26 October 2017 and 19 January 2018. Temperature measurements were made at 1 m intervals throughout the water column to the base of the borehole. All temperature profiles produce consistent readings and

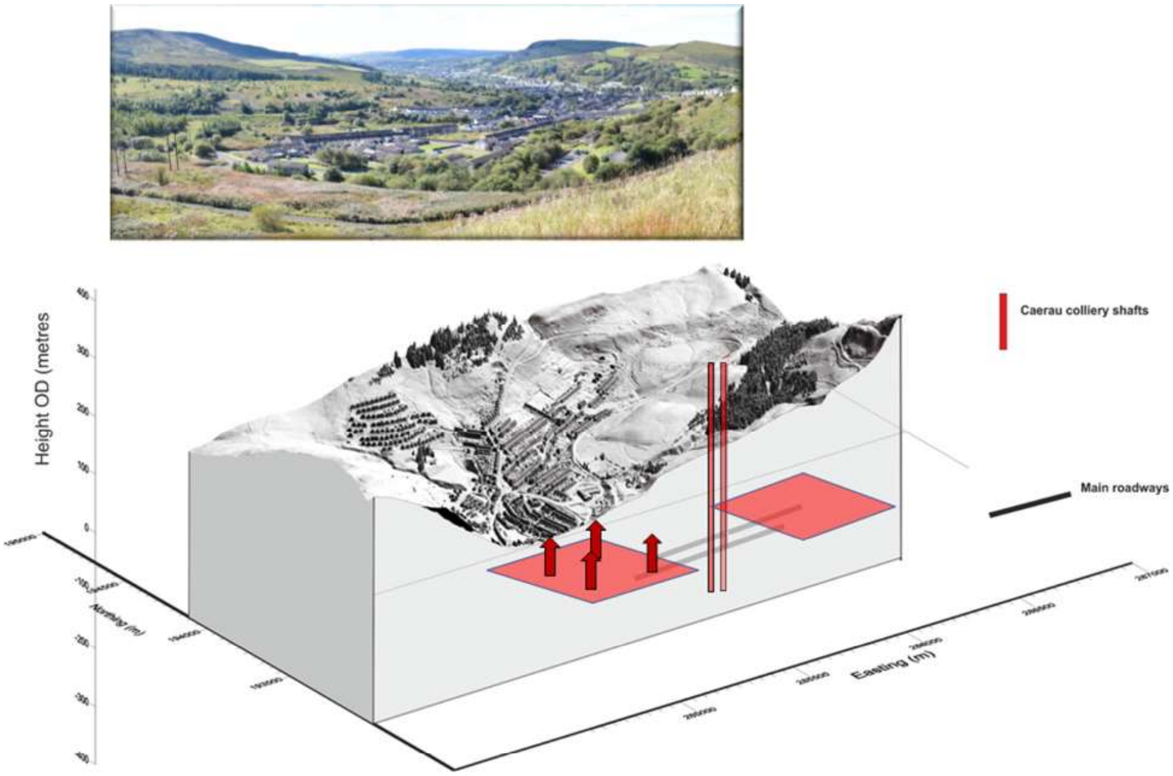

Fig. 6. Initial conceptual model of the location of the Caerau colliery North and South shafts and main roadway orientations in context of the valley geomorphology and housing. The photograph (P. Brabham) is taken looking SE down the Upper Llynfi valley. Data copyright: LIDAR data, Welsh Assembly government/NRW, LLE data web portal.

geothermal gradients (Fig. 11). The measured *in situ* temperature of the mine water within the slotted section of the borehole into the workings in the Six Foot horizon (between 212 and 229 m bgl) averages at 20.3°C at 230 m depth. Using an average annual air temperature of 8°C, an approximate geothermal gradient of 53°C km^{-1} can be estimated, which is significantly higher than the average UK geothermal gradient of 28°C km^{-1} (Busby *et al.* 2011).

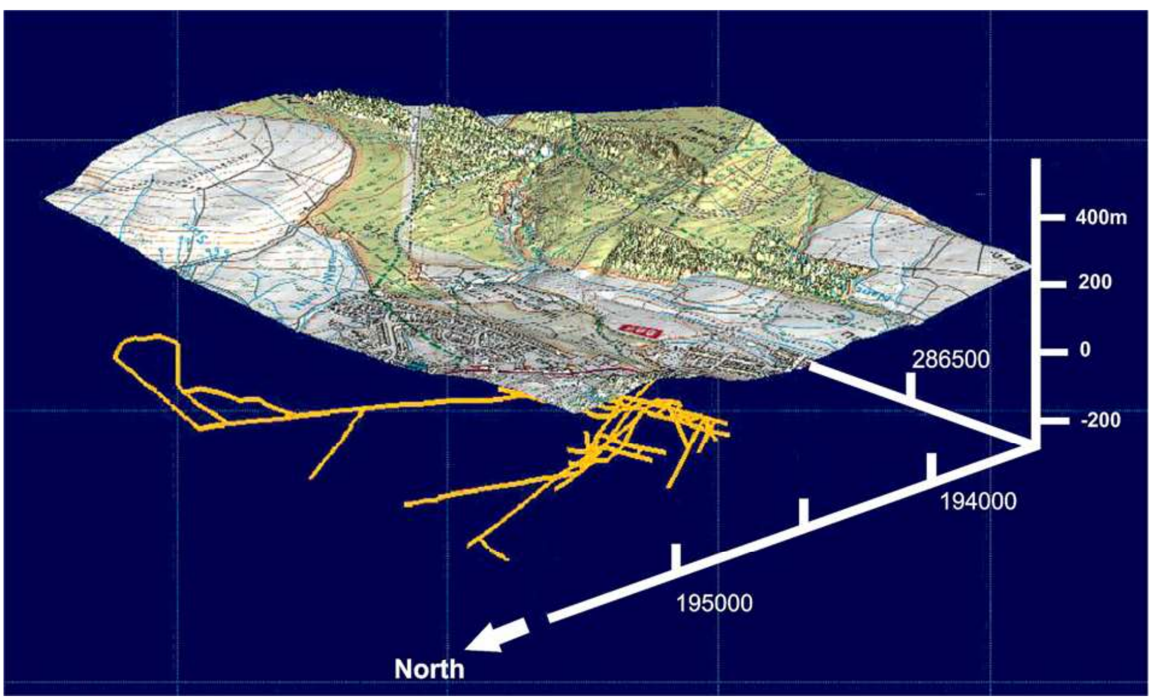

Fig. 7. Three-dimensional model of major underground roadways mapped at Caerau colliery. Reproduced with the permission of © The Coal Authority. All rights reserved.

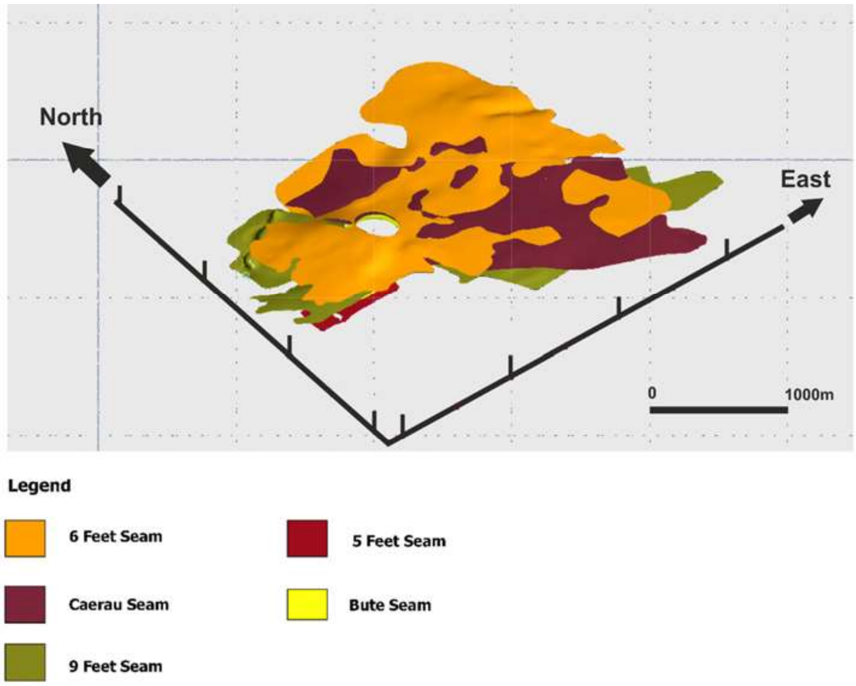

Fig. 8. Three-dimensional modelling of geospatial extent of known mineworking areas of five coal seams mined at Caerau colliery. The plug of unworked coal around the mine shafts is also illustrated. Reproduced with the permission of © The Coal Authority. All rights reserved.

Fig. 9. Drilling rig compound located in Caerau village, October 2018, with the landscaped Caerau colliery site observed behind the compound (photograph P. Brabham).

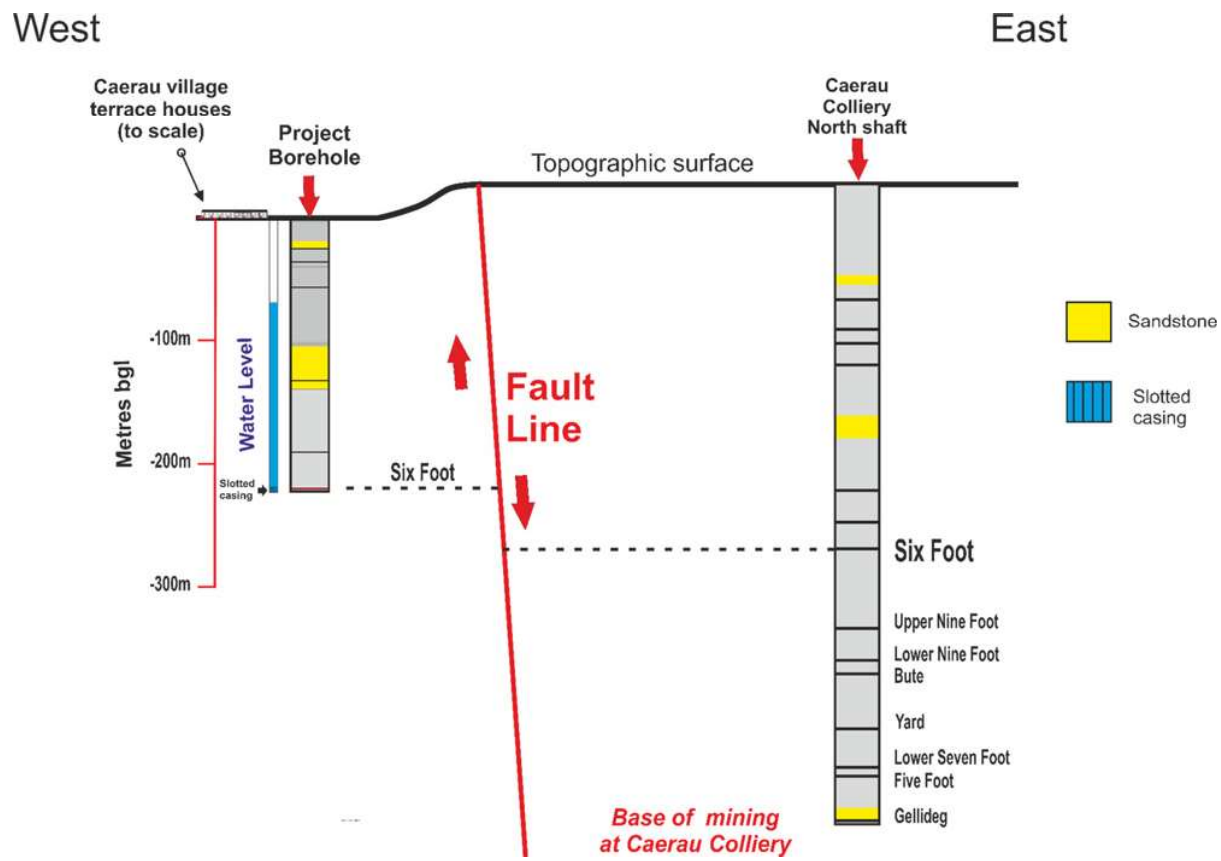

Fig. 10.

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Mine water chemistry

Water samples were collected from the completed borehole and the River Llynfi on 8 November 2017. The river is in the proximity of the drilling site; following regulations, the nearest water body must be monitored to ensure that no drilling fluid mix or any chemicals or materials related to the drilling leach into the river. This provided baseline river data for reference by a future mine water energy operation. The water samples were bailed from the boreholes using Insitu-Europe Hydrosleeves bags. Field parameters of temperature, pH, electric conductivity (EC), oxidation–reduction potential (ORP) and alkalinity were measured using an InSitu Europe SmarTroll multiparameter probe and a Hanna Instruments alkalinity measurement kit. The samples were filtered in the field using Fisherbrand Non-sterile Nylon Syringe Filter (hydrophilic 25 mm diameter nylon membrane, 0.45 µm) fitted on Fisherbrand Plastic PP Syringes, Luer Lock. The filtered samples were divided into inorganic and organic analysis. After filtering, a portion of the samples was acidified in the field with concentrated nitric acid and the samples were transported in an ice-cooled system to the laboratory. Aliquots of acidified water samples were analysed for cationic inorganic elemental analysis using a PerkinElmer inductively coupled plasma optical emission spectrometer and the un-acidified aliquots were used for anionic inorganic constitutions using a Dionex IC2000 ion-chromatography system.

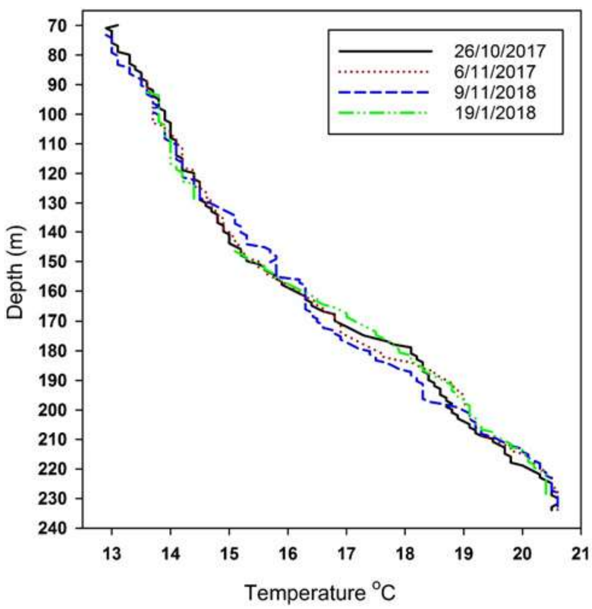

Fig. 11. Borehole temperature logs.

Table 2 shows the results of the water quality analysis of 8 November 2017. The River Llynfi river water displays similar chemical characteristics to the surface runoff waters in other areas of the South Wales Coalfield and the analysis confirms that no river contamination occurred as a result of the drilling process. The initial water samples collected from the borehole were muddy and grey in colour and it is assumed that the borehole water had not settled, but was disturbed by the drilling at the time of initial collection. Another set of water samples were collected over 2 months later on 24 January 2018. From the results, it was anticipated that the water sample collected at the end of the pumping period best represents the mine water. Although the pH of the borehole water sample remained around nine, the alkalinity increased from 268 to 720 mg l^{-1} within the short time period (8 November 2017 to 24

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Table 2. *Chemical characteristics of the waters from the borehole and River Llynfi*

Parameter	Borehole, 8 November 2017	River Llynfi, 8 November 2017	Borehole, 24 January 2018 (beginning of the pump test)	Borehole, 24 January 2018 (after pumping)
Temperature (°C)	13	10.8	9.8	17
pH	9	8	9.28	9
Eh (mV)	226	249	284	326
EC (µS cm^{-1})	698	83	635	1400
Total dissolved solids (mg l^{-1})	456	54	423	910
Dissolved oxygen (mg l^{-1})	3	10	3.66	1.84
Total alkalinity as $CaCO_3$ (mg l^{-1})	268	nd	nd	720
Phenolphthalein alkalinity as $CaCO_3$ (mg l^{-1})	198	nd	nd	390
CO_3 alkalinity as $CaCO_3$ (mg l^{-1})*	140	nd	nd	660
Sodium (mg l^{-1})	51	5.5	227	625
Calcium (mg l^{-1})	15	7.4	3.73	12.56
Magnesium (mg l^{-1})	3.5	5.1	1.14	6.65
Potassium (mg l^{-1})	8	2	7.81	21.27
Iron (total) (mg l^{-1})	0.12	0.6	nd	0.027
Manganese (total) (mg l^{-1})	0.19	0.17	0.01	0.055
Fluoride (mg l^{-1})	0.88	nd	2.38	1.56
Chloride (mg l^{-1})	10.21	nd	12.36	21.3
Sulphate (mg l^{-1})	26.98	nd	36.8	14.4
Nitrate (mg l^{-1})	nd	nd	0.5	0.97
Charge balance	0.027			
Charge balance error (%)	−3.8	–	–	34
Saturation index with respect to calcite ($CaCO_3$)	0.79	nd	nd	1.2

nd, not determined.
*Calculated value using phenolphthalein and total alkalinity values from Eaton *et al.* (1999).

January 2018). The alkalinity increase could be explained by the increase in alkali metals such as sodium (51–625 mg l^{-1}) and potassium (7.81–21.27 mg l^{-1}). The sample acquired from the borehole showed iron concentrations of 0.12 and 0.027 mg l^{-1}, which are lower than the measured values typically found in the coalfield (1.1–81 mg l^{-1} from Farr *et al.* 2016). This initial water sample analysis indicates that the water may not be a faithful representative of *in situ* mine water and may still be influenced by the drilling operation.

Most of the mine water drains in the South Wales Coalfield display pH value in the range of 6.83–7.83 despite the high concentrations of alkalinity (Farr *et al.* 2016). Low pH values in mine waters is caused by pyrite dissolution, which increases iron concentrations. In the long term, calcium minerals such as calcium carbonate dissolved by the low pH mine water would increase the alkalinity, which buffers the pH. Therefore, there could be two possible reasons for the considerable increase in pH, alkalinity and ion concentrations of the borehole water: (1) the low pH of mine water increases the dissolution of carbonate minerals, which buffers the acidity and controls the ion concentrations; (2) the low pH of the mine water dissolved the borehole grouting materials rapidly, which increases the pH and alkalinity values along with the alkali metal concentrations. The NaOH and KOH in the pore fluid of the grouting materials could be the main contributors to the high Na and K concentrations in the inflow water (Gascoyne 2002). Thus, the concentrations of Na and K increased over the 4.5 h period of pumping.

A Schoeller diagram was plotted for the water samples collected from the borehole to show the changes in the water type (Fig. 12). Further to chemical analysis, saturation index (SI) has been calculated for the sample taken on 24 January 2018 to indicate whether water is oversaturated, saturated or undersaturated with

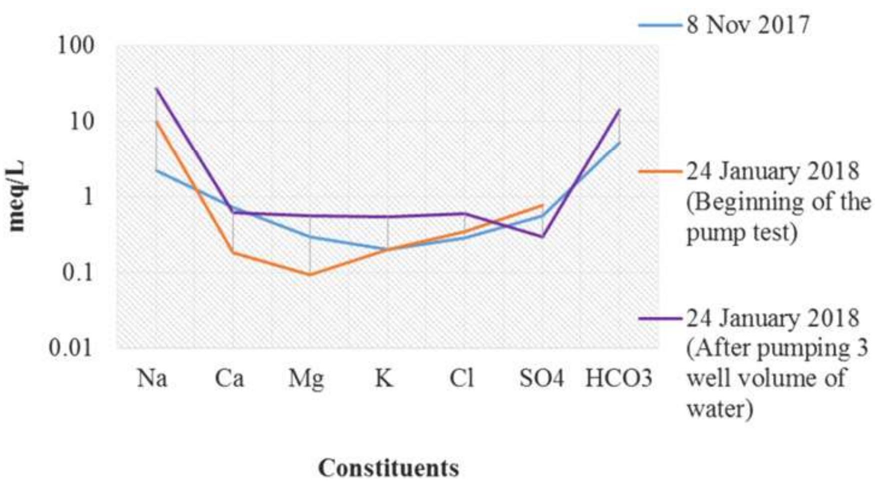

Fig. 12. Borehole water chemistry Schoeller diagram.

respect to calcite ($CaCO_3$). The SI indications are as follows: where the SI is >0, water is oversaturated with respect to calcite and scaling may occur; where the SI is <0, the water is undersaturated and corrosion may occur; where the saturation index is zero, the water is considered to be neutral. The SI value of the water sample from the borehole was found to be +1.2, which shows that the calcite is oversaturated and the water may have a tendency to form scaling but is non-corrosive (Langelier 1936). It is recommended that long-term pumping over a period of months should be carried out to obtain a better understanding of the mine water chemistry. However, a second borehole is required for reinjection, otherwise large costs would be incurred disposing of the mine water off-site by road tanker, as large volumes of un-remediated mine water would be unlikely to be allowed by NRW to discharge direct to the river Llynfi.

Assessment of the potential mine water reservoir at Caerau

From desk study research, the actual interconnected mining extent of the central coalfield of which Caerau colliery is just a small part could be as great as 68 km^2 in area. However, it is pure conjecture how much of the conduit roadways is still extant and offers interconnected hydrological pathways over this large area.

The borehole is predicted to have intersected one of the main roadways in the western area at the Six Foot seam horizon (Fig. 13). There are 13 mined coal seams at Caerau, all interconnected by a labyrinth of shafts and underground roadways. Using the 3D Caerau mine model, estimates can be made for the areal extent of mining void spacing for the known mined coal seams under the village. Workings in the Six Foot seam cover an area of 4.48 km^2, and workings in the deeper Caerau and Nine Foot seams cover areas of 2.8 km^2 and 3.2 km^2 respectively.

Discussion and conclusions

Geoscientists have traditionally seen mine workings as hazards and mine water as a pollutant, but do flooded mine workings now also represent a viable future geothermal resource in the UK? No researcher of the South Wales coalfield should ever underestimate the extent of abandoned mine workings extending over many square miles; often mining took place over 10 or more vertically stacked seam horizons. Individual collieries were often interconnected between adjacent topographic valleys by underground roadways and inter-seam workings. Every colliery mining layout is unique in three dimensions owing to the local stratigraphic sequence, bounding faults and mineral rights areas. All mines require an extensive desk study using primary abandoned mine plans to produce an accurate 3D initial conceptual mine model on which to plan any future exploration drilling programme.

Caerau mine is a typical medium-sized South Wales deep shaft colliery with an operational life lasting around 80 years. The mine had interconnected workings extending radially a few kilometres away from the shafts and stacked three dimensionally over 13 vertical seam horizons. Many kilometres of substantial, well-engineered access roadways are postulated still to exist underground. Hundreds of similar abandoned collieries exist throughout the South Wales coalfield (Cooke 2018); many collieries are less extensive than Caerau and some are significantly larger in extent (Fig. 1). A regional study has shown that interlinked mine workings around Caerau are extensive and thus could produce a large mine water catchment.

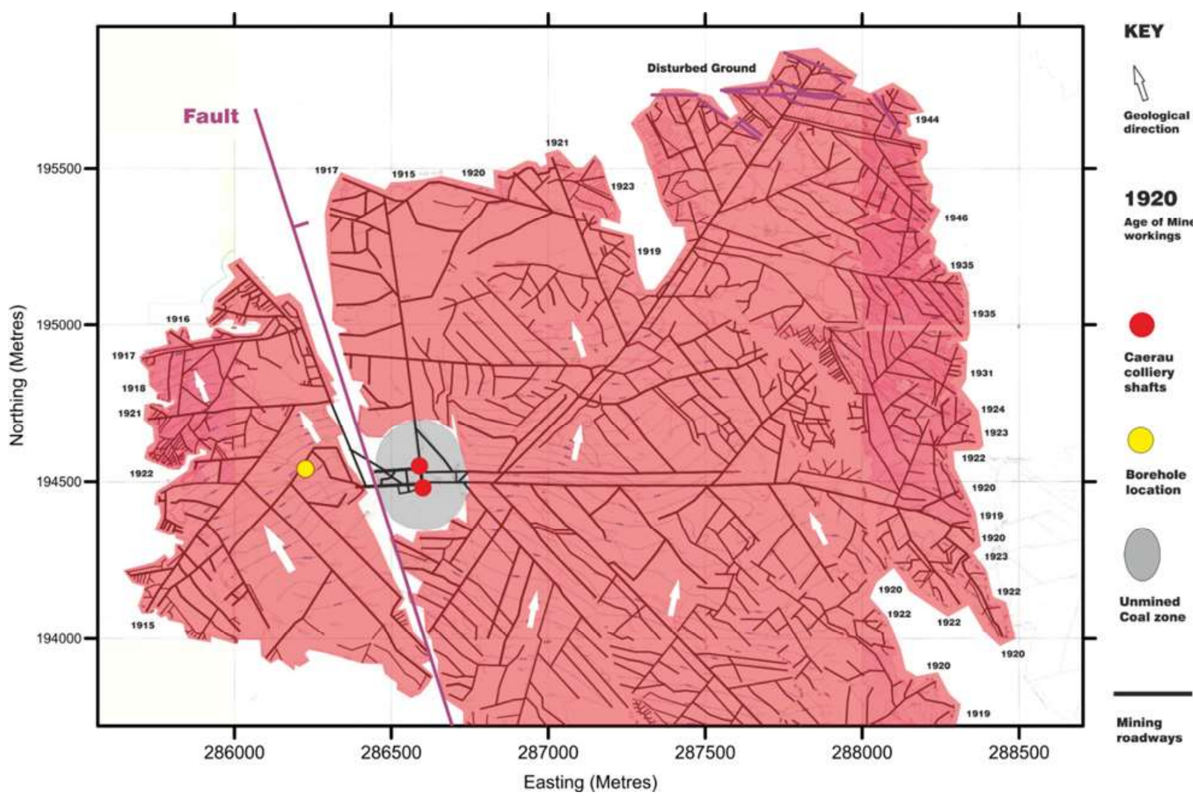

Fig. 13. Map of geospatial extent of mine workings in Six Foot seam at Caerau colliery showing context of borehole location (yellow circle). Interpreted and redrawn with simplification from Caerau colliery mine abandonment plans. Reproduced with the permission of © The Coal Authority. All rights reserved.

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An evaluation of Caerau colliery was carried out by an extensive desk study incorporating 3D geo-referencing and mosaicking of 36 historical mine abandonment plans, and from this an initial conceptual geological and mining model was created. An exploratory borehole was located on accessible land to target mine workings at the Six Foot horizon and drilling successfully encountered a flooded void space at a depth of 224.30 m bgl. The water sampling and testing stage proved technically challenging over a tightly constrained drilling period with a small diameter borehole. In retrospect, more time and equipment should have been allocated in planning for a hydraulic flushing programme to better test the water recovery rate achievable within the mine void.

Mine water temperatures measured at the basal slotted section of the borehole average at 20.3°C and the water level was at 92 m bgl. The measured geothermal gradient of 53°C km^{-1} is significantly higher than those observed in other UK coalfields and this should contribute significantly to the improved efficiency of the proposed community heat network project. This higher than expected water temperature is a trade-off against the depth to the water being deeper than anticipated and thus the energy required to pump water to surface being greater.

These conclusions are based on only one exploratory borehole, and additional mine water chemical analyses and pump test flow rate measurements require the drilling of a second exploration borehole ideally at a larger production diameter. An array of extraction and reinjection boreholes drilled into mine workings beneath Caerau could provide warm (≥20°C) mine water as the thermal energy source for a mine water district heating network. For the community heating energy demand at Caerau an abstraction–reinjection open-loop system with several abstraction and reinjection boreholes spatially distributed within the mine working conduits would probably be the most viable option. Other options include the incorporation of energy storage capacity within the system.

The discovery of flooded mine workings containing mine water at higher than expected temperatures makes this district heating project a positive proposition. There are still unknowns about the volumetric extent of the mine water reservoir and the heat capacity of the mine water flow regime within the 3D labyrinth of mine workings. A second, larger diameter, commercial diameter borehole is recommended to be drilled to allow high flow rate pump testing and more chemical analyses over a longer time period. If these second stage results prove favourable, then this could lead on to a production heat from mine water district heating system being designed and constructed in the Upper Llynfi valley.

Acknowledgements The authors wish to thank the residents of Caerau for embracing the project and tolerating an exploration drilling rig located in the heart of their village. We would also like to thank M. Jenkins and C. Williams and their engagement team members of Bridgend County Borough Council, plus the FLEXIS/SEREN community engagement team, particularly J. Lewis and A. Koj. M. Trewhella of Kensa Contracting Ltd, D. Tucker and SPECIFIC team at Cardiff Metropolitan University are all valued for their project team discussions. J. Crooks and P. Thorn of the Coal Authority are thanked for their collaboration in project discussions. APEX Ltd and R. Davies (Rhondda Geotechnical Services) are acknowledged for their expertise in the successful completion of the borehole. We also thank the anonymous reviewers whose comments have greatly improved this paper.

Funding The work described in this paper has been undertaken by the Geoenvironmental Research Centre (GRC), Cardiff University, led consortium. The study was commissioned by Bridgend County Borough Council, Contract Reference B477, to carry out a feasibility study with the support of the Heat Network Delivery Unit (HDNU), whose mandate is to support the development of low-carbon district heat networks. Work was also supported by the Welsh Government under the REW framework Agreement Number NPS-PS-0003-14 and Flexis project, which is funded by the Welsh European Funding Office (WEFO).

Author contributions PJB: Writing – Original Draft (Lead); HT: Funding acquisition (Lead), Validation (Supporting), Writing – Review & Editing (Supporting); GF: Formal analysis (Equal), Investigation (Equal), Methodology (Equal), Validation (Equal), Writing – Review & Editing (Equal); RF: Project administration (Equal); RS: Formal analysis (Supporting); SS: Formal analysis (Supporting); MM: Project administration (Lead).

Scientific editing by Jonathan Smith; Phil Renforth

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