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Karstified and fractured Lower Carboniferous (Mississippian) limestones of the UK – A cryptic geothermal reservoir

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Abstract: Karstified and fractured Lower Carboniferous (Mississippian) limestones of the UK have been evaluated for their geothermal potential. This wholly undeveloped resource is calculated to be in excess of 26 million GWh (95 EJ) for the P_{90} case and as much as 35 million GWh (129 EJ) for the P_{50} case for six regions in England and Wales, ranging in scale from Kent at 0.04 million GWh (P_{50}) to Northern England at 15 million GWh (P_{50}). The evaluation used three sources of evidence to assess the distribution, current burial depth, likely temperatures and transmissivity of these limestones. Seismic and outcrop data, well logs and cores from drilled wells and water chemistry data from thermal springs were used to demonstrate the presence of deep, water bearing, permeable limestones. Geothermometry calculations using spring-water composition data provided clues about temperatures at which the issuing water equilibrated with its original host rock indicating that water now reaching the surface had acquired its solutes at temperatures significantly in excess of 30 °C and depths much greater than 1 km. The UK uses about 2.5 EJ per annum yielding a resource to use ratio of 40-50 years assuming no natural inflow or reinjection of cooled water for reheating.

Keywords: geothermal energy, karst, Mississippian carbonates, fractured reservoir

1. Introduction

The hot springs at Bath, UK were used in antiquity by Iron Age humans and subsequently by Romans (Gerrard 2007). Much more recently, in 1919, the first oil well was drilled in the UK at Hardstoft in Derbyshire (Craig et al. 2014). Both the hot springs and petroleum accumulation at Hardstoft owe their existence to the presence of interconnected macro porosity within deeply buried, karstified and fractured Mississippian limestones. Indeed, Carboniferous limestones host almost all of the UK's cave systems and its tepid and hot springs. These same limestones (and dolostones) have also been the target for oil and gas exploration onshore and to a lesser extent offshore UK (Gluyas & Bowman 1997; DECC 2013; Total 2007). The interconnected pore spaces in these limestones and associated dolostones are not primary but secondary and tertiary, formed through a combination of fracturing and dissolution of the carbonate minerals. Much of the near surface pore space in the Mississippian limestones of the UK comes from a combination of uplift and geologically recent karstification during the Ice Ages. However, such recent karstification cannot be implicated as the cause of secondary porosity and enhanced permeability in all Mississippian limestones and dolostones of the UK.

Recognition that not all interconnected porosity in UK Mississippian limestones was created by Ice Age karstification (Bathurst 1961; Walkden & Williams 1991; Vanstone 1998) is important because it allows situations to be conceived in which porous and permeable limestones occur at substantial depth beneath the Earth's surface and that such limestones may contain hot water and hence be developed as geothermal energy systems (Busby 2014). Thus, the aim of this study was to determine the distribution of porous and permeable limestone at depth in the UK and to make a preliminary assessment of the geothermal resource.

2. Methods and database

Three different, complimentary approaches were used to obtain evidence that Mississippian limestone geothermal systems may exist at depth in the UK. We attempted to identify all occurrences of porous and/or permeable Mississippian limestones and dolostones from drilled wells and other subsurface information sources such as mapped cave systems. Field measurement of temperature for connate and meteoric waters was undertaken and where possible they were sampled and their chemistry was analysed. The water composi-

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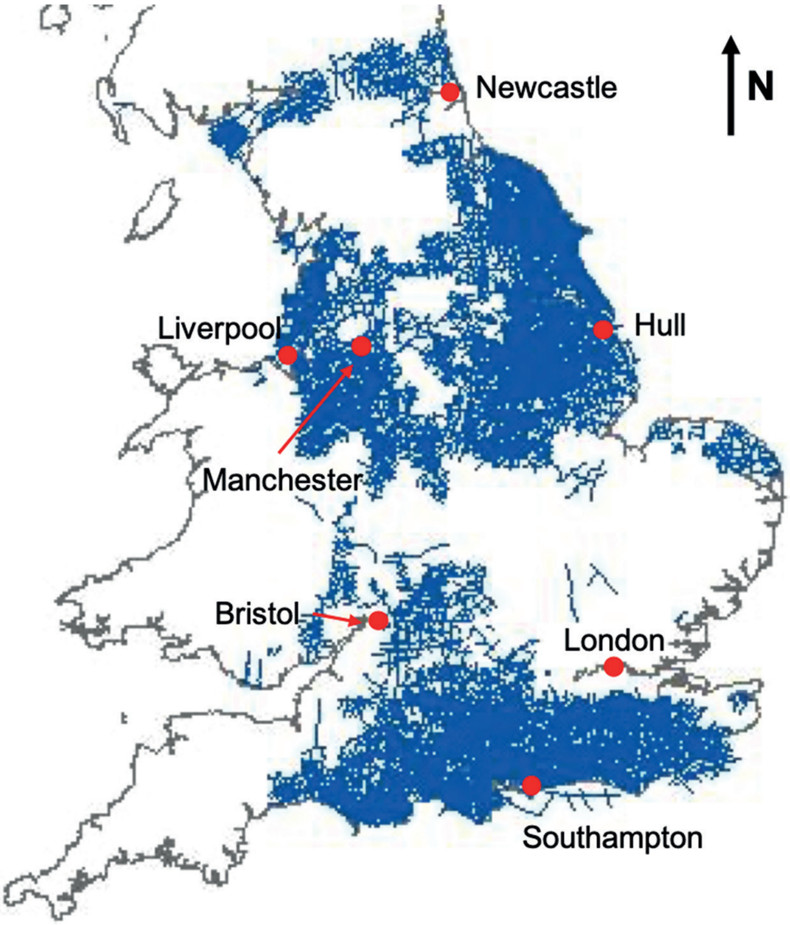

Fig. 1: UK Onshore Geophysical Library 2D Seismic Lines. Approximately 20 % of the lines were used in this study.

tional data were then used to back-calculate the temperatures at which the dissolved elements present in the sample equilibrated with their source rocks (geothermometry).

Post-Mississippian unconformities were identified using outcrop and seismic data (Fig. 1). The seismic data were tied to petroleum exploration and other wells known to penetrate into Mississippian limestones. Unconformities identified at outcrop and on seismic data were regarded as candidate karst surfaces. The seismic and wellbore data together with published information on thickness of the limestones were also used to map the extent of the Mississippian limestones in each of six areas in England and Wales in which Mississippian strata are known to occur. All of these data were then used to calculate the gross and net rock volumes and pore volume in the limestones of each basin from which it is possible to estimate the geothermal resource in each basin.

3. Geology of Mississippian limestones in the UK

Limestones and dolostones of Carboniferous (Mississippian) age occur throughout the UK. They crop out in the Midland Valley of Scotland, the Pennines of northern and central England and adjacent areas, western England together with North and South Wales. Boreholes and mines have also encountered Mississippian limestones down dip from areas of outcrop along with additional areas known only from borehole and geophysical data in southeast (Kent) and southern England (Fig. 2). Deposition of Mississippian limestones, mudstones and minor sandstones occurred during active rifting (Waters et al. 2009) and the palaeogeographic setting for the interval has been well established.

The thickness of the Mississippian strata varies substantially. At the Seal Sands borehole in the Stainmore Trough (basin) North East England 3442 m of Mississippian section was penetrated without reaching the base (Johnson et al. 2011). Elsewhere on former shelfal areas the interval may only be a few hundred meters thick, thinning to zero on contemporaneous highs. Attenuation of the Mississippian strata by erosion is also common (Figs. 3 and 4). The oldest unconformity surface identified is of Brigantian/Pendleian age (Lancashire coast, central Pennines, North Yorkshire; Fraser & Gawthorpe 1990). Further, Pennsylvanian age unconformities were identified in sections mapped from the English West Midlands. In many areas Mississippian carbonates occur below base Permian or Triassic sandstones and mudstones, while in southern England, Mississippian strata are

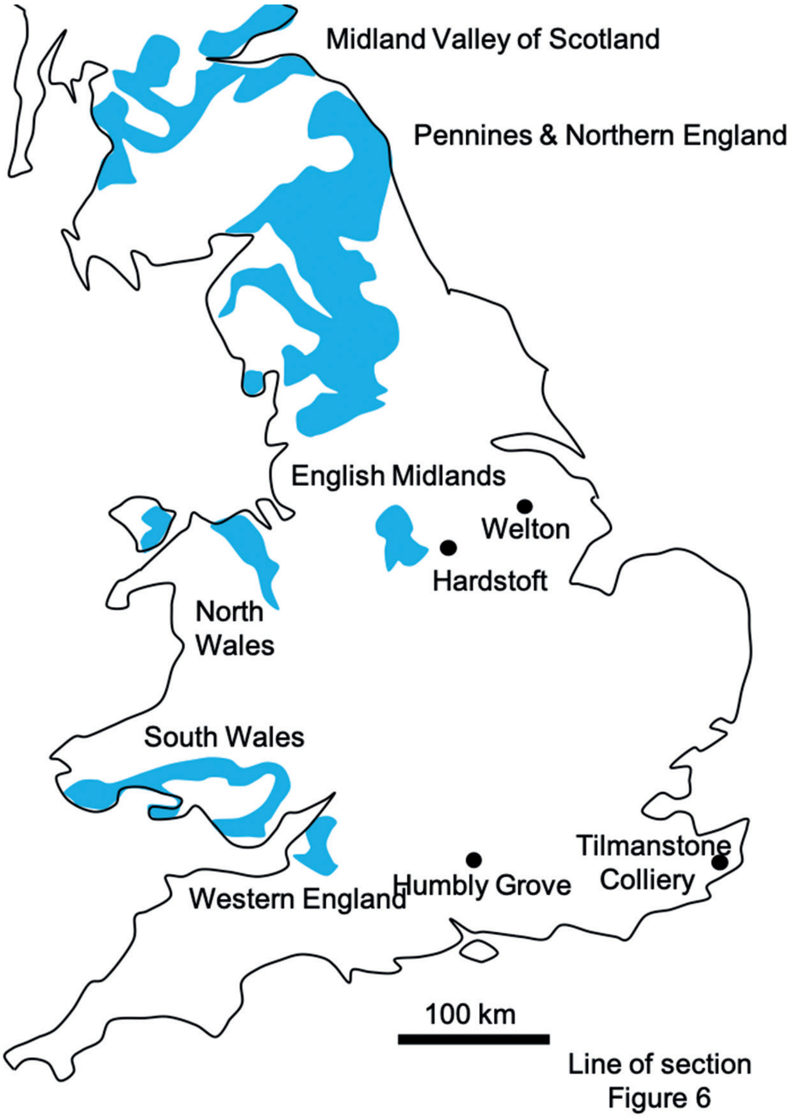

Fig. 2: Outcrop, near surface and selected borehole penetrations of Mississippian limestones in the UK.

overlain by Liassic or younger Middle Jurassic strata. Where Mississippian strata crop out, they have, of course, a present-day erosion surface.

The lithological composition of the Mississippian strata change from south to north (Francis 1991; Leeder 1992). The South of England, South Wales and the English Midlands contain sequences which are predominantly carbonates (limestone, dolostone and calcareous mudstones). In northern England and the Scottish Midland Valley, the interval is heterolithic. In addition to carbonates, these areas also contain sandstones, clay dominated mudstones, siltstones and coals (Francis 1991).

During the Mississippian, the landmass now known as the UK lay close to the equator. A marine transgression occurred at the beginning of the Carboniferous across an undulose Late Devonian surface (Davies et al. 1991). The transgression progressively drowned upland areas. For example, in the North Pennines, the oldest sedimentary rocks of Holkerian (Visean) age are located above the Weardale Granite compared with the adjacent basins that were inundated much earlier during the Hastarian (Tournasian) (Burchette et al. 1990). In South Wales, Southern England, North Wales and the Midlands lagoonal, marine carbonates accumulated on the pre-existing highs while the corresponding basinal areas comprise interbedded limestone turbidites and hemipelagic shales many of which are rich in organic matter. In northern England and Scotland, the depositional environment was typically marginal marine to paralic that produced the mixed carbonate, clastic and coals, known locally as Yoredale cycles (Tucker et al. 2003; Booth et al. 2020).

Deposition of the Mississippian rocks occurred during active rifting (Fraser & Gawthorpe 1990). Half graben developed in Scotland, northern and central England. In southern England, south of the Wales-Brabant Massif deposition

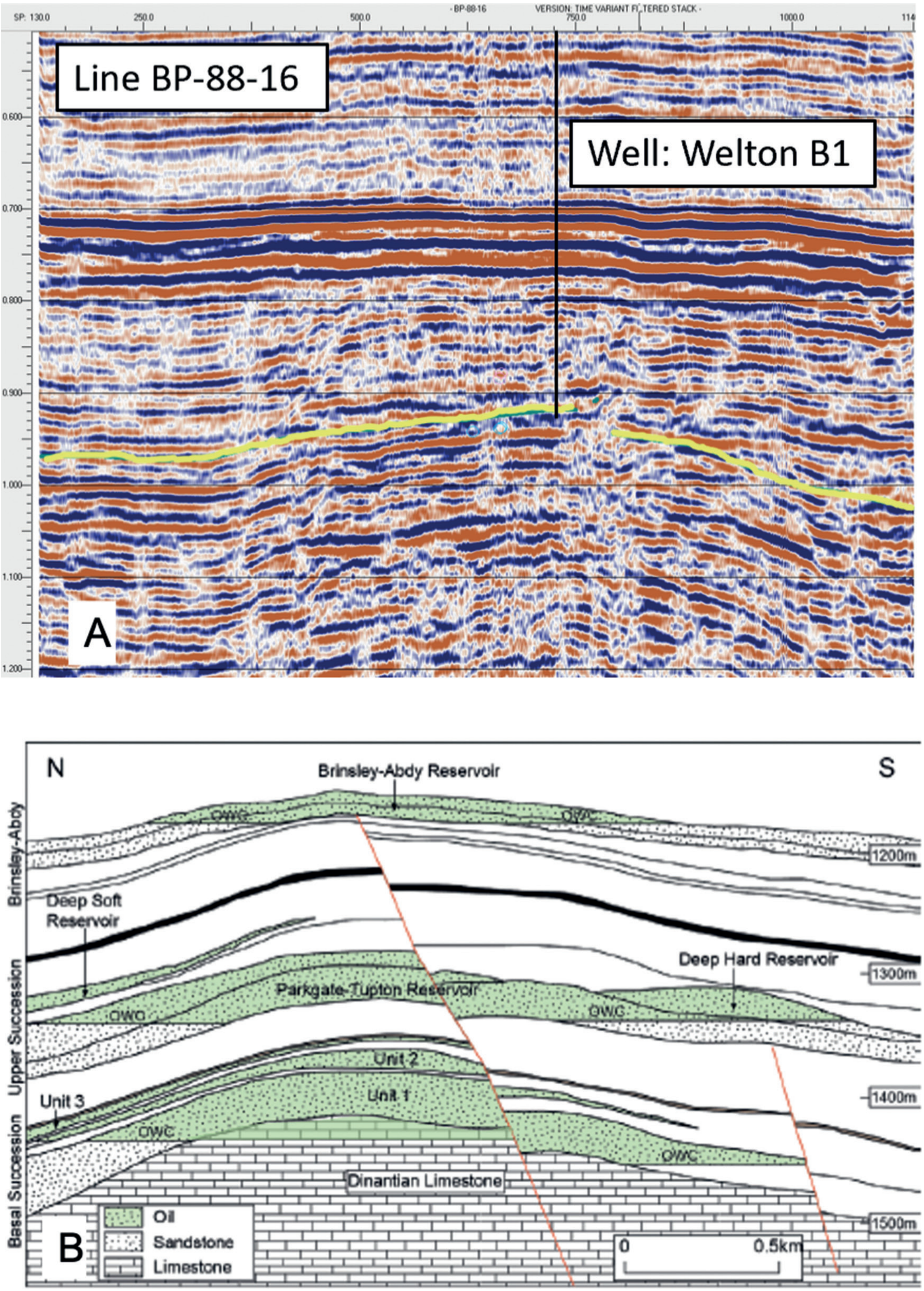

Fig. 3: (**A**) Interpreted seismic line across the Welton oilfield (BP-86-16), top Mississippian (yellow); (**B**) geological cross section of the Welton oilfield showing onlap of basal Pennsylvanian sandstones onto the Mississippian (Dinantian) limestones (modified from Hirst et al. 2015).

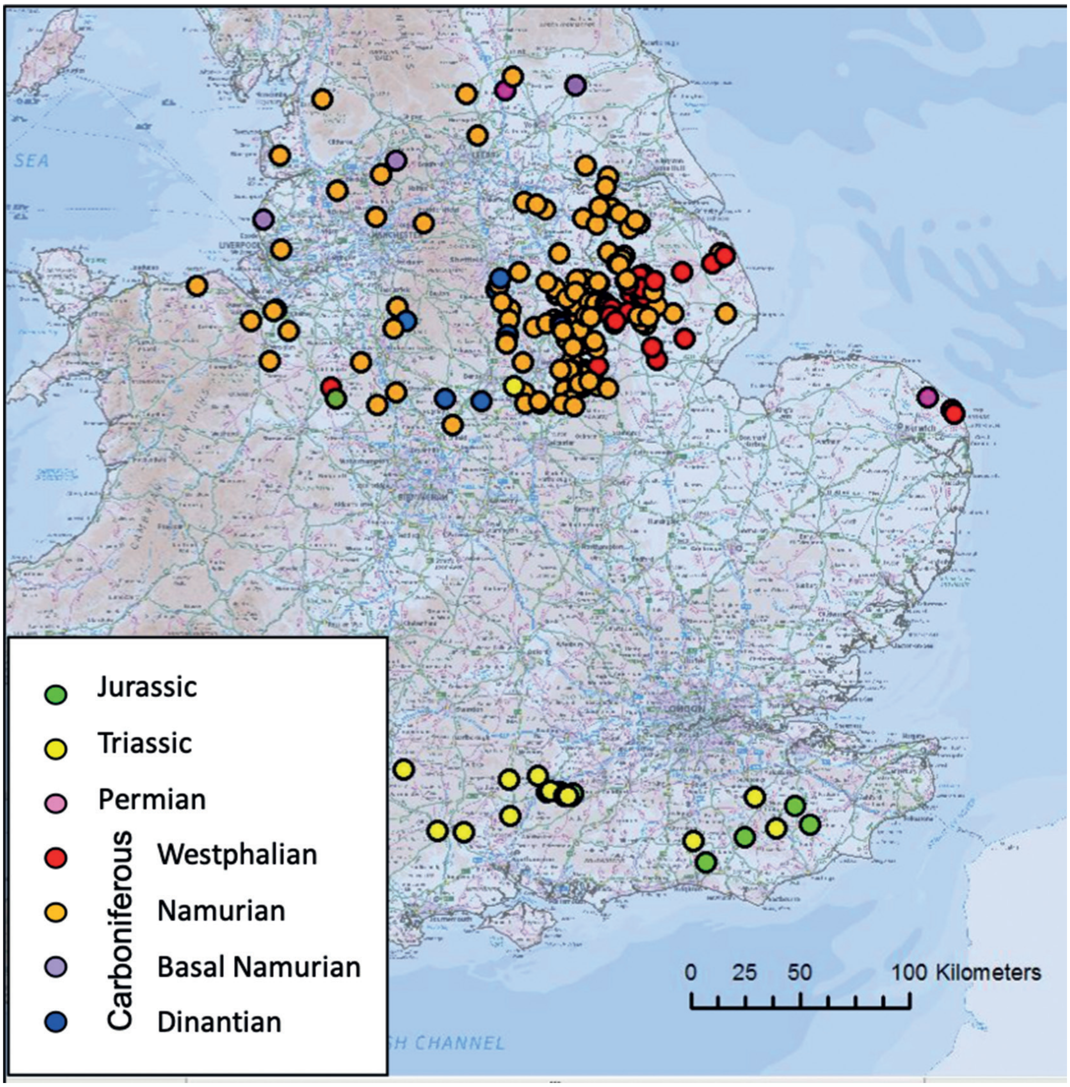

Fig. 4: Unconformity surfaces on top (eroded) Mississippian limestones in the UK annotated by age of overlying strata. Mapped from 2D seismic data.

Fig. 5: Folded and fractured Mississippian limestone turbidite beds, Ape's Tor, North Staffordshire (photograph by J. Gluyas).

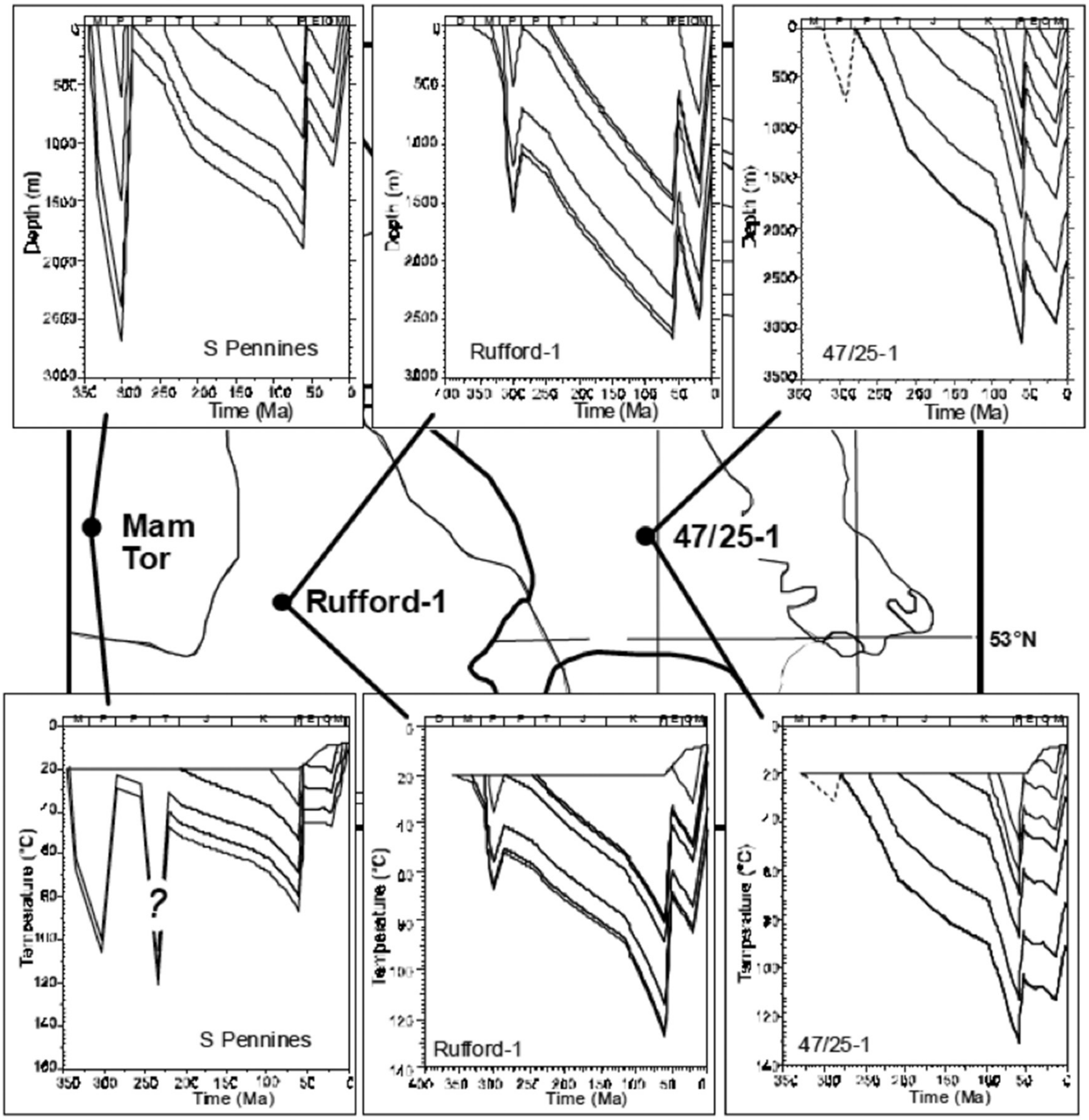

Fig. 6: Burial and uplift history of the Carboniferous in the East Midlands (from Green 2003).

occurred on the northern margin of a deep-water marine basin (Burchette et al. 1990). For the Scottish and northern England basins (Midland Valley, Northumberland Trough, Stainmore Trough and its extension into the North Sea) subsidence was rapid but was matched by sedimentation rates. As such the depositional environment was maintained as shallow marine to paralic. In central England and the Southern North Sea, sedimentation lagged behind subsidence and while contemporaneous highs (shelves) accumulated carbonate shoals with fringing reef-like complexes, adjoining basin areas received a lesser input of shelf-derived carbonate turbidites and hemipelagic muds (Fig. 5). These basinal areas may contain in excess of 3000 m of Mississippian mudstones and limestones (Andrews 2013). In southern England and South Wales deposition of carbonates dominated.

Syn-rift subsidence gave way to post-rift subsidence in the Pennsylvanian, although some areas including the Welton oilfield (Fig. 3) show evidence of either base level fall or more likely continued rotation of fault blocks into the very latest Mississippian as an unconformity can be identified locally at this level. The thickness of the post-rift sediment interval is substantial (several kilometres; Waters et al. 2009) and comprises a shallowing and regressive sequence of prodeltaic and deltaic lithologies including a variety of sandstones, mudstones and coals. Towards the end of the Carboniferous, continental collision from the south produced the Variscan Orogeny, attendant uplift and consequent multiple unconformities in the uppermost Carboniferous interval. Erosion levels were such that from time to time the Mississippian limestones were both exposed and eroded. Similarly, basal Permian and Triassic rocks lie with unconformity on

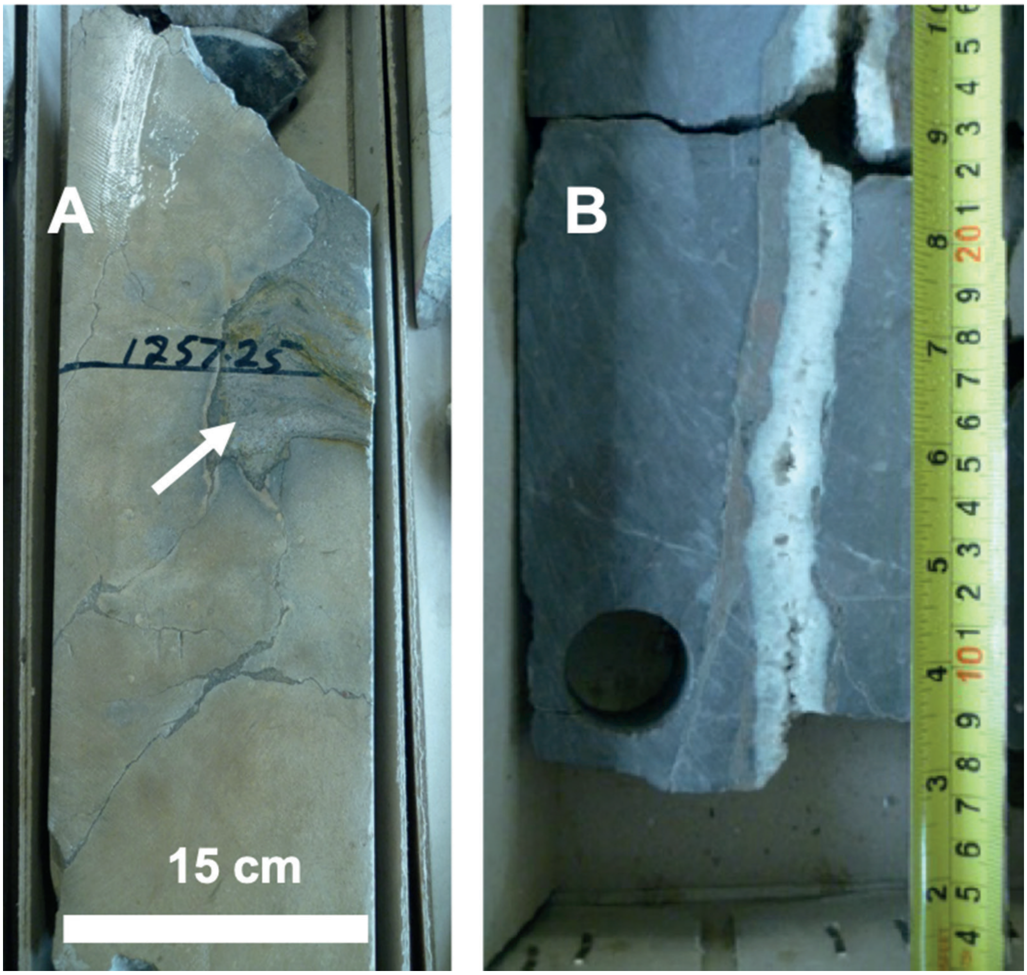

Fig. 7: Core from (**A**) Nettleham, Lincolnshire well B2 (drilled depth 1257.25 m below rotary table) showing infilled karst cavity (arrowed), (**B**) Humbly Grove showing a partially cemented fracture.

eroded Mississippian limestone. Indeed, the famous Wookey Hole cave system in the Cheddar area of western England has developed largely in the limestone rubble deposited in Early Triassic times in deep valleys eroded into the Mississippian limestones (Simms 1990).

Further south in Hampshire, the Mississippian limestones are overlain by Rhaetian (Upper Triassic) calcareous sandstones in the Humbly Grove oilfield (Gluyas et al. 2020) and at Stroud in Gloucestershire, fissured Carboniferous limestone is overlain by Middle Jurassic limestones (Donovan et al. 2005). It is probable that the Cretaceous was a period of subsidence and burial across much of the UK, while development of the North Atlantic from the Palaeocene led to uplift and eastward, downward rotation on a national scale.

Possible burial and uplift histories for areas now occupied by Mississippian limestone outcrop and subcrop are shown in Fig. 6 (Green 2003). The unconformity surfaces which affect the Mississippian limestones include several within the Carboniferous, Permian, Triassic, Liassic/Middle Jurassic, Early Tertiary and of course Pleistocene (Fig. 4).

Direct evidence for karstification and fracturing can be found at outcrop and in cores cut in wells (Fig. 7). The possible karst features identified include dissolution enlarged fractures and sediment filled vugs, exemplified by high rate fluid flow from springs and rapid mud losses sustained when drilling wells (Table 1).

4. Reservoir properties of Mississippian limestones

There are few porosity and permeability data available for cores cut in the Mississippian limestones in the UK. At core-plug (small core cut into main core for reservoir quality measurement) scale (2 × 8 cm), porosities up to about 30% have been recorded but more commonly lie in the range 1–5% (Bouch et al. 2004; Total 2007). The highest porosities typically occur in dolomitised rock (Gawthorpe 1987) as roughly biomouldic pores. Commonly such porosity is vuggy and poorly interconnected yielding permeabilities of typically less than 10 mD and often less than 1 mD (approx.

10^{-14} and 10^{-15} m^2 respectively). Reservoir quality data from Grove 1, a failed oil exploration well in the East Midlands record a porosity range of 1.4–12.5% (average 7.8%) and permeability of 0.04–10.1 mD (arithmetic average 0.56 mD) from vuggy biomouldic dolostone. Comparable porosity and permeability data from Nettleham 1 are 5.3% and 1.3 mD and from Nettleham 2 15.3% and 3.3 mD (maximum value).

Despite the low porosity and permeability measurements made on core and hand specimens, Carboniferous limestones of the UK are classified as both major and minor aquifers depending upon their location (Allen et al. 1997; Jones et al. 2000). Flow rates vary considerably between different locations. The so-called Great Spring encountered when the Severn Railway Tunnel was built (opened in 1886) flows at 60,000 m^3 per day and there are plenty of springs in southern Wales, Somerset and Derbyshire that exceed 10,000 m^3 per day of water flow (Newson 1973). Deep well tests for both petroleum and water also indicate substantial flows albeit considerably less than that of shallow springs (Table 1). Wells in both Cheshire and Nottinghamshire have produced flow rates measured in hundreds of cubic meters per day.

Such flow principally occurs along fracture systems many of which may have been enhanced by dissolution. These high permeability intervals are difficult to core (leading to poor core recovery) and thus under-represented in the core analysis data. In addition, the Mississippian limestones

Table 1: Flow rates from Mississippian limestones in wells and springs (measured and calculated temperature for well data; from Hirst 2017), calculated equilibrium temperature data for springs.

Well	Location	Region	Depth interval	Flow rate	Equilibrium temperature
			m true vertical depth sub-sea level	m^3 day^{-1}	°C measured (calculated)
Severn Tunnel, Great Spring	Monmouthshire	Avon & South Wales	surface spring	60000	
Cheddar Springs	Somerset	Avon & South Wales	surface spring	40900	
Banwell Spring	Somerset	Avon & South Wales	surface spring	31800	
Schwyll	Bridgend	Avon & South Wales	surface spring	22100	
Rodney Stoke/Honeyhurst	Somerset	Avon & South Wales	surface spring	11400	
Milton	Pembrokeshire	Avon & South Wales	surface spring	6800	
Sherborne	Somerset	Avon & South Wales	surface spring	6500	
Ffrydian Twrch	Powys	Avon & South Wales	surface spring	4500	- (78)
Ffynon Gisfaen	Powys	Avon & South Wales	surface spring	3000	33-78
Taff's Well	South Wales	Avon & South Wales	surface spring	87.2	21 (78)
Bath (3 main springs)	Bath	Avon & South Wales	surface spring	1440	44-47 (66)
Humbly Grove	Hampshire	Southern England	>1337	>1337	>60
Eakring/Duke's Wood	Nottinghamshire	East Midlands	717	9.0	40
Hardstoft	Derbyshire	East Midlands	1000	0.6	30
Nettleham 1	Lincolnshire	East Midlands	1414–1480	3.2	45
Nettleham 2	Lincolnshire	East Midlands	1411–1450	15.2	45
Nocton 2	Lincolnshire	East Midlands	886	0.5	43
Welton	Linclonshire	East Midlands	1599		45-60
Grove 3	Nottinghamshire	East Midlands	2290–2375	35.0	70
Strelley 1	Nottinghamshire	East Midlands	1312–1410	317	44
Cropwell Butler 1	Nottinghamshire	East Midlands	956–981	13.6	46
Bingham 1	Nottinghamshire	East Midlands	881–900	91.4	
Redmile 1	Nottinghamshire	East Midlands	927–936	1.14	
Calow 1	Derbyshire	East Midlands	1121–1133	252	
Ridgeway	Derbyshire	East Midlands	883	455	49
Bardney Well 1	Lincolshire	East Midlands	1508–1558	25.2	56
Cold Hanworth 1	Lincolnshire	East Midlands	1665–1720	29.3	71

Table 1: cont.

Well	Location	Region	Depth interval m true vertical depth sub-sea level	Flow rate m³ day⁻¹	Equilibrium temperature °C measured (calculated)
Langar 1	Nottinghamshire	East Midlands	957–986	8.6	
Holmesford	Derbyshire	East Midlands	surface spring	44600	
The Limestone Scheme	Derbyshire	East Midlands	surface spring	22600	
Buxton (St. Anns Well)	Derbyshire	East Midlands	surface spring	914	28 (68)
Matlock Spa (E Bank Rising)	Derbyshire	East Midlands	surface spring	43.2	21 (64)
Matlock Fountain Bath	Derbyshire	East Midlands	surface spring	1022	20 (60)
British Legion Spring	Derbyshire	East Midlands	surface spring	806	12 (62)
Recreation Ground	Derbyshire	East Midlands	surface spring	17.3	13 (57)
Stony Middleton	Derbyshire	East Midlands	surface spring	115.2	18 (61)
Bradwell Spring	Derbyshire	East Midlands	surface spring	57.6	12 (61)
Beresford Dale Spring	Derbyshire	East Midlands	surface spring	144	14 (70)
Lower Dimindale Spring	Derbyshire	East Midlands	surface spring	360	28 (68)
Matlock Ball Eye Quarry	Derbyshire	East Midlands	surface spring	129.6	25 (71
Meerbrook Sough	Derbyshire	East Midlands	surface spring	68256	16 (68)
Dunsley Springs Site 1	Derbyshire	East Midlands	surface spring	2231	- (60)
Harrogate	Yorkshire	East Midlands	Surface spring		(89-125)
Milton Green 1	Cheshire	W Midlands & N Wales	1448-1476	304	47
Gilsland Spa	Cumbria	Northern England	surface spring	2.85	10 (68-80)
Catlowdy Holy Well	Cumbria	Northern England	surface spring	4.32	14 (92)
Clifton Wells	Cumbria	Northern England	surface spring	43.2	10 (72)
Denton Mains	Cumbria	Northern England	surface spring	1.90	12 (77)
Palmer Hill Holywell	Cumbria	Northern England	surface spring	2.16	10 (78)
Seal Sands	Cleveland	Northern England	4127		>100

at Humbly Grove in Hampshire are known to provide pressure support for production of gas from the Triassic Rhaetian reservoir interval (Gluyas et al. 2020).

Much but by no means all of the flow in limestones is in the shallow subsurface through open fractures and fissures some of which have been enlarged by karstification. The fracture porosity may be 1% (Shepley 2007) or less but such porosity is clearly well connected. Calculation of the additional porosity added through karstification is fiendishly difficult and the estimations of such porosity change dependent upon the method used as well as the scale of observation. Calculations based upon analogue systems of buried karst in Hungary and China suggest that total karst porosity may be around 1% and unlikely to exceed 4% (Albert et al. 2015; Dai et al. 2017), moreover Zhao et al. (2015) noted that only the upper 70 to 100 m or so of limestone beneath the bounding unconformity was karstified. Fracture porosity, although often critical for permeability enhancement is typically <0.5%.

5. Evidence of geothermal potential

Direct Evidence

The hottest springs in the UK are located at Bath Spa in Southwest England, with a measured temperature range of 44–47 °C (Gallois 2007). Elsewhere in the UK there are tepid springs from which water issues at 20–30 °C (Table 1).

Temperature measurements are recorded when wells are drilled to explore for or produce petroleum. The data available from wells that have encountered Carboniferous limestones and dolostones are also presented in Table 1. Here, temperatures vary between about 30 °C and 100 °C, with the hottest wells being those in which the Carboniferous limestones are the deepest. Temperature data are not available for the Seal Sands well (Johnson et al. 2011) but with a depth of greater than 4 km, the Carboniferous Yoredale sequence temperatures at the bottom of the well will likely exceed 100 °C (Busby 2011).

Indirect Evidence – Geochemical Evaluations

In addition to direct temperature measurements, it is also possible to deduce equilibration temperature information from geochemical data. Existing geochemical data have been obtained from published literature, the Environment Agency and other public domain sources. An initial approach undertaken has been the application of solute geothermometry which involves assessing the ratios between specific dissolved ions within the water to calculate the temperature at which the connate water was in equilibrium with the host rock. This is done using formulae derived from studies pursued by various authors. Six different geothermometers were applied: Na-K-Ca with Mg correction (Fournier & Potter 1978), K-Mg (Giggenbach 1988), a cationic composition geothermometer (Nieva & Nieva 1987), Mg-Li (Kharaka & Mariner 1989), Na-Li (Kharaka & Mariner 1989) and quartz-chalcedony (Arnorsson et al. 1983).

However, some of the derived temperatures proved spurious being either below the freezing point of water or in a few instances approaching 200 °C. Remaining results yield equilibrium temperatures compatible with derivation of waters from deeper within the basins (Table 1).

For example, application of the geothermometer technique to three samples from the hot springs at Bath indicates that although current measured temperatures are 44–47 °C the water equilibrated with the rock at ~60 °C (Adams et al. 2021). This is corroborated by the multicomponent geothermometry technique which suggests a temperature between 60 and 75 °C. These temperatures are compatible with inferred origin of the water as derived from rain falling on the Mendip Hills about 30 km to the southwest, percolating downwards to about 2 km and then rising through a fracture system at Bath (Gallois 2007).

A second example is from Harrogate in Yorkshire where highly saline, sulphurous springs issue at 14 °C (Brassington 2003). The high chloride content of the water has been used to calculate an equilibrium temperature in excess of 73 °C (K-Mg estimate) and possibly in excess of 100 °C using Li data in the Na-Li geothermometer and for which the host rock is not known.

6. UK geothermal resource in Mississippian limestones

In order to calculate the geothermal resource in UK Mississippian limestones we have used the following devices and made the following assumptions.

The Mississippian outcrop and subcrop of England and Wales was divided into six regions (Fig. 8): Avon and South Wales, Southern England, Kent and the English Channel, East Midlands, West Midlands and North Wales, and Northern England. The area of Norfolk is also underlain by Mississippian limestones but the area is small and has a low population density and as such no calculations of heat resource have been made since there will be little demand. Similarly, only the onshore portions of the Kent and East Midland Areas have been evaluated as hot water offshore will have no value.

The depth ranges from 1 km to base Mississippian are shown on Fig. 8. The area of each region was calculated, recognising that in most instances the derived figure will be an underestimate of the actual area of subcrop (and outcrop) given lack of data in the deepest parts of the basins. The heat resource has only been calculated for areas of each region which are deeper than 1km and therefore highly unlikely to contain potable fresh water. In the absence of reliable top Mississippian surfaces, no attempt has been made to derive area-depth plots. Instead a slab model has been used for reservoir thickness to give gross rock volume and the mean depth of the slab at depths greater than 1 km to calculate the mean temperature.

It has been assumed that the vast bulk of the connected porosity occurs within fractures and a mid-point value of 1% has been used. Correspondingly, net to gross has been set at 90%. The pores are assumed to be water filled and hence a water saturation of 100% has been used. There are a few small petroleum accumulations but their presence will not appreciably impact the mean water saturation.

Water has been assumed to be extracted from the subsurface but not replenished. That is to say only the heat content of the water in place was used to calculate the heat resource. No attempt is made to extract heat from the rock matrix.

The rejection temperature for water from which heat is to be extracted is variable and based upon the UK's Metrological Office annual surface-temperature variation for each of the regions. That is to say, with lower temperatures in winter more heat is extracted from the geothermal fluid than in summer. The surface temperatures and hence rejection temperatures can vary between a low, winter temperature of 1 °C in eastern England to 24 °C high in summer in southern England.

The ranges for area, thickness, net to gross, porosity and temperature and rejection temperature are given in Table 2.

A Monte Carlo simulator (Crystal Ball™) was used to calculate the geothermal resource for each area and for the UK as a whole (Table 3 and Fig. 8).

A sensitivity analysis on the Monte Carlo outputs indicates that the main uncertainties are thickness of the Mississippian limestones and assigned porosity small variations in these parameters can lead to large variations. Given the synrift setting for the Lower Carboniferous and paucity of well penetration data, thickness estimation was fraught. Similarly, the assigned fracture porosity mean value of 1% and maximum value of 2% propagates through to a 100% volume and hence heat resource.

7. Discussion

Combining spatial geophysical data and core and well logs with geothermometry has allowed us to highlight regions where fractured and karstified geothermal targets exist, the temperatures that might be expected and the resource in place. As far as we are aware this is the first attempt to quantify the geothermal resource from Mississippian limestones in the UK. The UK geothermal potential was first assessed in

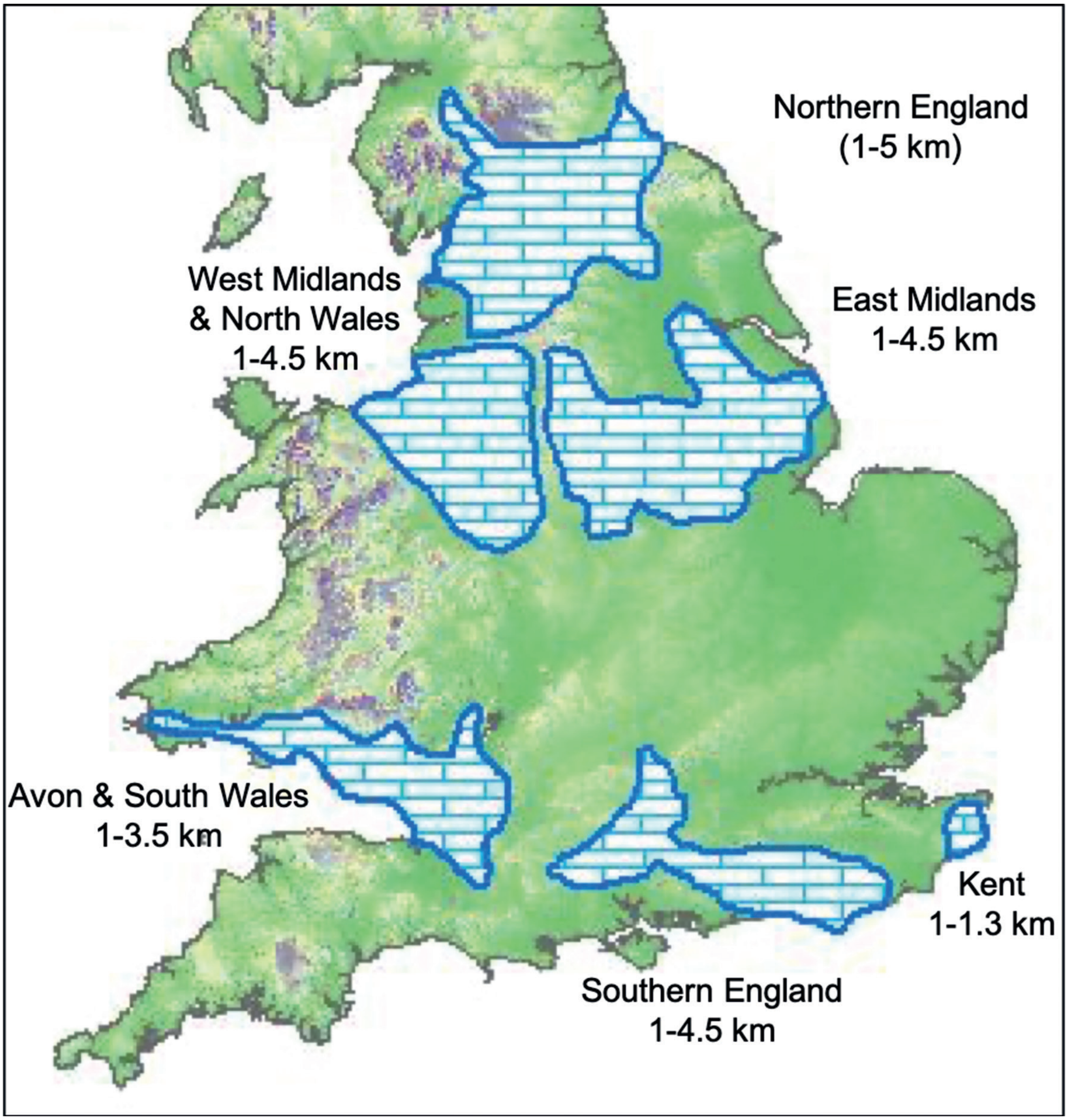

Fig. 8: Geothermal resource regions for the Mississippian limestones of England and Wales. Areas were calculated for the parts of the regions where the limestones are at greater than 1 km present day burial depth. Maximum depths to base Carboniferous limestones are approximate and based upon Narayan et al. 2018.

response to the oil crisis (Downing & Gray 1986) and subsequently by Busby (2014) who estimated the composite geothermal resource of Permo-Triassic basins in the UK to be about 200 EJ. This value is approximately twice that of the P_{90} Carboniferous limestone resource and one and a half times the P_{50} resource. Other factors common to both this and the Busby (2014) study are explored below.

Water has been assumed to be extracted from the subsurface but not replenished. That is to say only the heat content of the water in place was used to calculate the heat resource. In the resource estimated, no attempt is made to extract heat from the rock matrix; therefore the heat resource estimated is likely to be a conservative one. For geothermal exploitation, doublets comprising a pair or pairs of wells would be drilled for abstraction and reinjection of the geothermal fluid following heat extraction. The point being that the absolute volume of geothermal fluid present in the reservoir is not crucial as long as flows are sufficient to meet energy demand and there is sufficient time for re-injected water to heat back up to avoid the risk of short-circuiting.

Developing such projects will require deep drilling and an economic appraisal is essential before determining targets. Where the fluid temperature is at 60 °C or more, this source could be fed directly into a heat network (via a heat exchanger) whereas lower temperatures from shallower depths will likely require a heat pump to boost temperatures.

Table 2: Input parameters for Monte Carlo simulation.

	Range	**Distribution**	**Units**
Avon and S Wales			
Area	5000-5700-6000	triangular	km^2
Thickness	100-800-1500	triangular	m
Net:gross	0.8-0.9-1.0	triangular	fraction
Porosity	0.1-0.1-0.2	triangular	fraction
Water saturation	1		fraction
Mean temperature	60+3.5	normal	°C
Rejection temperature	2-24	uniform	°C
Kent			
Area	360-400-440	triangular	km^2
Thickness	15-200-250	triangular	m
Net:gross	0.8-0.9-1.0	triangular	fraction
Porosity	0.1-0.1-0.2	triangular	fraction
Water saturation	1		fraction
Mean temperature	60+6	normal	°C
Rejection temperature	2-24	uniform	°C
East Midlands			
Area	10,000-11,400-12,000	triangular	km^2
Thickness	200-1100-2000	triangular	m
Net:gross	0.8-0.9-1.0	triangular	fraction
Porosity	0.1-0.1-0.2	triangular	fraction
Water saturation	1		fraction
Mean temperature	90+9	normal	°C
Rejection temperature	2-23	uniform	°C
Southern England			
Area	6000-6700-7000	triangular	km^2
Thickness	15-200-250	triangular	m
Net:gross	0.8-0.9-1.0	triangular	fraction
Porosity	0.1-0.1-0.2	triangular	fraction
Water saturation	1		fraction
Mean temperature	100+10	normal	°C
Rejection temperature	2-24	uniform	°C
W Midlands and N Wales			
Area	7000-8000-8500	triangular	km^2
Thickness	200-1100-2000	triangular	m
Net:gross	0.8-0.9-1.0	triangular	fraction
Porosity	0.1-0.1-0.2	triangular	fraction
Water saturation	1		fraction
Mean temperature	90+9	normal	°C
Rejection temperature	1-20	uniform	°C
Northern England			
Area	9000-10,400-11,000	triangular	km^2
Thickness	200-1800-3400	triangular	m
Net:gross	0.8-0.9-1.0	triangular	fraction
Porosity	0.1-0.1-0.2	triangular	fraction
Water saturation	1		fraction
Mean temperature	90+9	normal	°C
Rejection temperature	1-20	uniform	°C

Table 3: Calculated geothermal resource for regions in the UK. P_{90} and P_{50} are probabilities, EJ = Exajoules (10^{18}).

Area	P_{90} geothermal resource (x 10^6 GWh)	P_{50} geothermal resource (x 10^6 GWh)	P_{90} geothermal resource (EJ)	P_{50} geothermal resource (EJ)
Northern England	7.463	14.980	26.8	54
East Midlands	5.221	9.762	18.8	35
West Midlands and North Wales	3.748	7.110	13.5	26
Avon and South Wales	1.115	2.373	4.0	8.5
Southern England	0.930	1.181	3.3	4.2
Kent	0.028	0.039	0.1	0.14
Composite resource	26.330	35.858	94.8	129.1

A trade off therefore exists between drilling depth and whether a direct or heat pump system is used, essentially CAPEX versus OPEX. Additionally, if the cost of carbon is considered then the higher temperature targets could offer a very low carbon option for heat supply (although there would be an energy demand associated with water pumping for both deployments).

It is also not known at this stage if wells drilled into deep Mississippian limestones would flow naturally or require pumping. For one at least, Humbly Grove (Gluyas et al. 2020) the Carboniferous limestone aquifer supporting gas production from the Triassic reservoir interval is known to be very responsive.

8. Conclusions

Mississippian limestones and dolostones in the UK have not previously been considered as a target for geothermal energy development. Here we have demonstrated that they can be highly productive despite low matrix permeability because of the presence of transmissive fractures, some enlarged by karstic processes operating at various times since the deposition of the limestones. We have also highlighted their occurrence and extent at depths suitable for geothermal energy exploration and estimated the resource in place of between 26 and 35 million GWh (probability of exceedance for P_{90} and P_{50} cases). Based on the UK's current heat demand this resource would last for 40–50 years assuming no natural inflow or reinjection of cooled water for reheating. In practical terms, only areas of the UK underlain by this resource could access such heat and the economically viable resource is likely to be considerably smaller. Nonetheless, Mississippian limestones could supply a sustainable heat supply for significant parts of the UK. Confirmation of the viability of such geothermal reservoirs in the UK will require new wells to be drilled and tested.

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