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A thermal maturity map based on vitrinite reflectance of British coals

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Abstract: A compilation of new and previously published vitrinite reflectance (R_0) data from Carboniferous coals constitutes the most comprehensive map of reflectance across Great Britain. Values of R_0 range from 0.38 to 3.29%, recording an ambient thermal maturity in the early oil window (standard reference point for reflectance studies), modified by elevated heat flow in northern England and along the Variscan orogenic front. The map provides a context for other geological datasets.

Supplementary material: A statistical summary of vitrinite reflectance data is available at https://doi.org/10.6084/m9.figshare.c.4529969

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We present a map of vitrinite reflectance data for Great Britain (Fig. 1). The map is the most comprehensive that is publicly available. Maturity data previously compiled by the National Coal Board were obtained from the content of volatile matter (Creedy 1986, 1988). A recent limited compilation of data from some sedimentary basins in Britain (Linley 2014) is accessible only by subscription. The map presented herein incorporates data from several minor coalfields not included in earlier compilations. The data plotted are exclusively from coals of Great Britain of Carboniferous age (Fig. 2). They are collated from published sources and newly measured samples. The published sources include information hitherto not reported in geological literature.

Use of vitrinite reflectance data

Vitrinite reflectance is a measure of the cumulative thermal maturity of coalified plant remains. The use of vitrinite reflectance data is diverse, and includes the following examples: (1) estimation of remaining potential to yield hydrocarbons, including conventional oil and gas, and shale gas (e.g. Hackley & Cardott 2016); (2) determination of palaeogeothermal gradients, by measuring changes in vitrinite reflectance with depth (e.g. Marshall *et al.* 1994); (3) assessment of broad regional variations in maturity owing to metamorphism and/or tectonic history (e.g. Creaney 1980); (4) assessment of local variations in maturity owing to igneous intrusions (e.g. Bishop & Abbott 1995); (5) measurement of displacement across major faults through contrast in maturity across the fault (e.g. Cavailhes *et al.* 2018); (6) assessment of provenance of clasts containing coaly matter, in sedimentary successions (e.g. Vandenberghe 1976); (7) identification of potential sites for exploitation of geothermal energy (e.g. Manning *et al.* 2007); (8) identification of palaeogeothermal anomalies to guide mineral exploration (e.g. Maynard *et al.* 2001); (9) combination with apatite fission-track data to deduce the thermal histories of basins (e.g. Bray *et al.* 1992); (10) assessment of provenance of coal fragments encountered in archaeological sites (e.g. Smith 1996).

The wide-ranging applicability of vitrinite reflectance data makes a database of compositions valuable.

Methods

There are 14 new analyses in this study, from Inninmore Bay, East Trodigal, High Tirfergus, Uddingston, Arran, Ascog (Bute), Kello Water, Jenkin Beck, Tan Hill, Rowanburn, Wrexham, Hanwood, Pembroke and Midsomer Norton. Samples for new vitrinite reflectance analyses were crushed and then mounted in epoxy resin and polished, according to the method of Bustin *et al.* (1990). Samples were analysed in reflected, non-polarized, monochromatic light ($\lambda = 546$ nm) under oil immersion ($\nu = 1.518$) using a Zeiss Axioskop MPM400 microscope equipped with MPS 200 system by J&M Analytik AG. The standard materials used to calibrate the microscope depend on the coal rank and are spinel with relative reflectance (R_r) of 0.426%, sapphire with R_r of 0.585%, YAG (yttrium–aluminium–garnet) with R_r of 0.905%, GGG (gadolinium–gallium–garnet) with R_r of 1.72 and cubic zirconia with R_r of 3.09. About 50 measurements for each sample were made to statistically constrain heterogeneities in the analysed kerogen.

Data

The vitrinite reflectance (R_0) values range from 0.38 to 3.29% (Figs 3 and 4; Table 1 and supplementary material Appendix I). The distribution of values (Fig. 3) shows that a majority of samples have R_0 values in the range up to 0.80%. A smaller group are in the range 0.80–1.0%, and a third group in the range from 1.0% upwards has a distinct geographical distribution (Fig. 4). Depths given for samples in Table 1 are estimated based on information (where available) on coal seam depth, depth of extraction or depth of the colliery from where the samples were taken. In general, samples from boreholes are stratigraphically well constrained, whereas spoil and *ex situ* samples are less accurate. Borehole sampling also provides a better opportunity to sample at greater depths than what may be achievable for samples collected through conventional shaft sinking

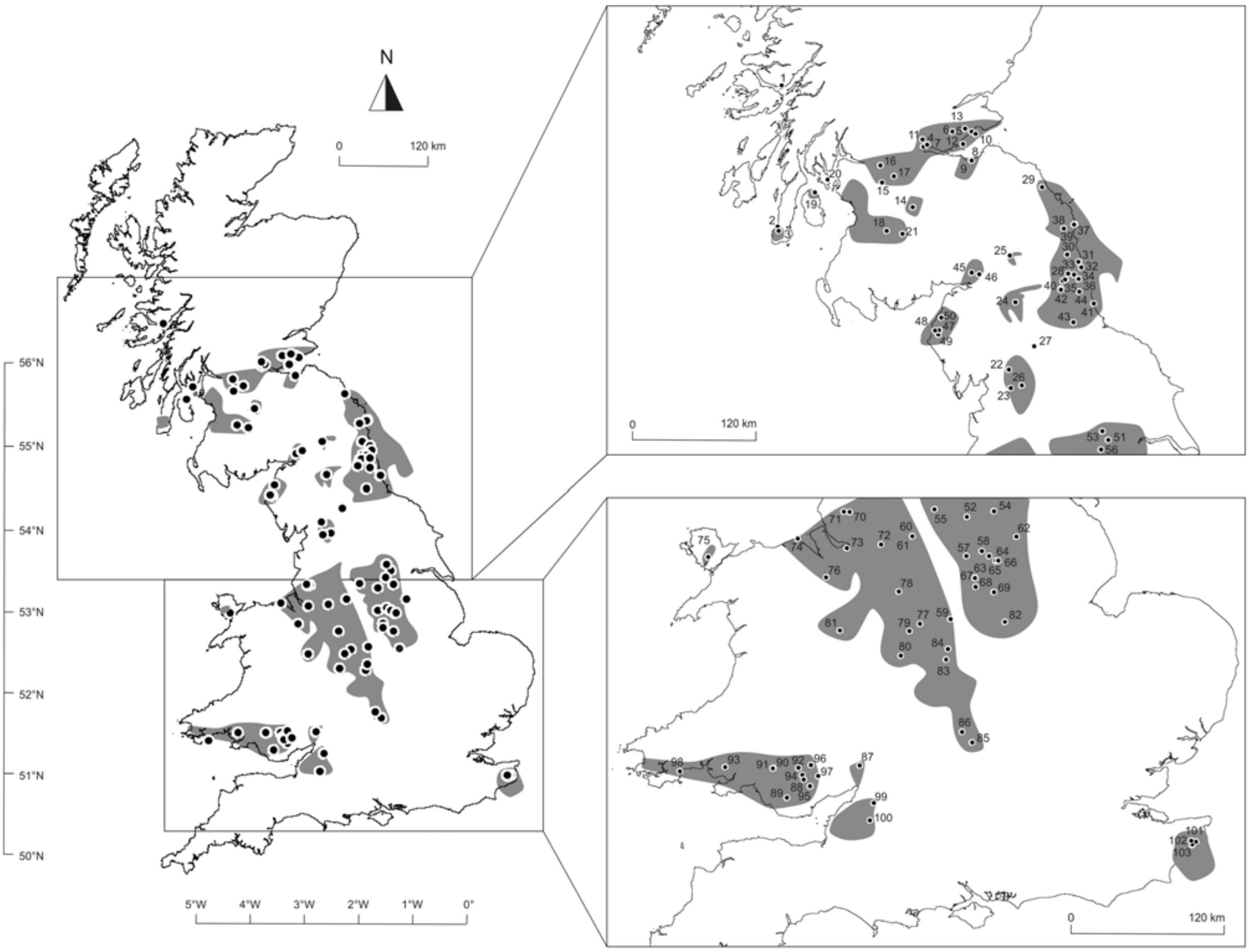

Fig. 1. Map of Great Britain, showing exposed British coalfields (grey), sample localities (black dots) and identification numbers (see insets) used in Table 1 (base map after British Geological Survey 1999).

excavation. Depths presented are also subject to available data in references or obtainable colliery or site information. The depths presented do not account for any uplift, burial or erosion, and therefore may not fully represent the maximum burial experienced by the samples whilst *in situ*. No correlation is observed between estimated sample depth and R_0 %.

Age	Stage	Substage	Lithostratigraphy		Substage
	Stephanian	Cantabrian			
307 Ma	Westphalian	Asturian	Pennine Coal Measures Group	Warwickshire Group	
		Bolsovian			Upper Coal Measures
		Duckmantian			Middle Coal Measures
		Langesttian			Lower Coal Measures
312 Ma	Namurian	Yeadonian	Clackmannan Group	Yoredale Group	
		Marsdenian			
		Kinderscoutian			
		Alportian			
		Chokierian			
		Arnsbergian			Upper Limestone Formation
		Pendleian			Limestone Coal Group
326 Ma		Brigantian	Visean		Lower Limestone Formation
	Visean	Asbian			
		Holkerian		Border Group	

Fig. 2. Stratigraphy of coal-bearing Carboniferous section, UK (Waters *et al.* 2007), including units identified in Table 1.

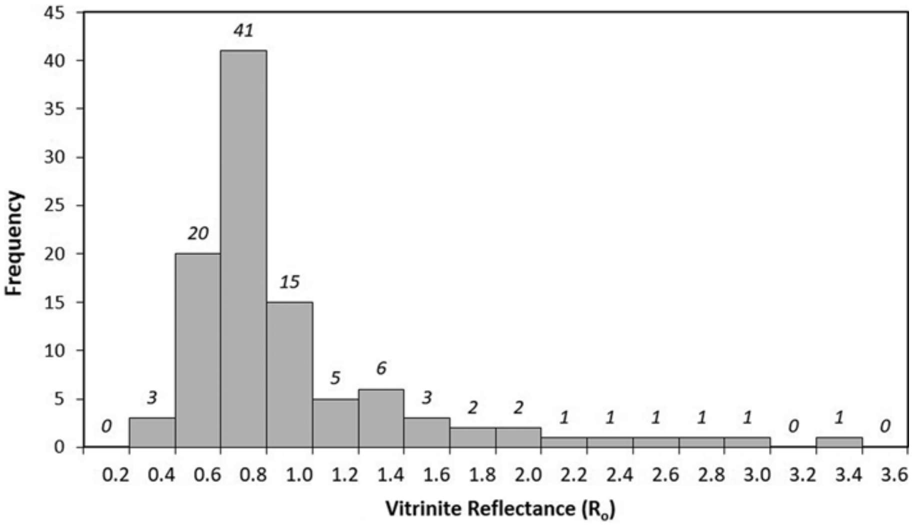

Fig. 3. Distribution of reflectance values for total dataset.

Discussion

Reflectance data presented here are constrained to the highest possible accuracy, in terms of considering R_0 % standard deviation of each sample for newly acquired data (see Appendix I), and assessing the adequacy of methods used in published data. However, it is important to note that when interpreting the values presented, there are inherent expected variations of reflectance with vertical depth in a Coal Measures sequence and in the source data referenced. Data presented and assumptions made here represent conservative interpretations, which can be more rigorously tested with additional data (e.g. more samples for areas where one or few samples have been analysed) and studies on a given sample, region or stratigraphic section. The values below 1.0% are typical of sedimentary basins in western Europe, where Carboniferous sediments are in the window of oil generation. The oil generation window extends from 0.5 to 1.3%, equivalent to coals that are classified as bituminous (Tissot & Welte 1984; Petersen 2006), typically formed at 2–6 km depth and 50–150°C (Bjørlykke 2015; Mani *et al.* 2017).

The values above 1.0% are from regions that have experienced anomalous localized heating. The samples from South Wales, the Bristol region and Kent form a linear belt in the vicinity of the Variscan (Hercynian) orogenic front. During orogenesis, hot fluids

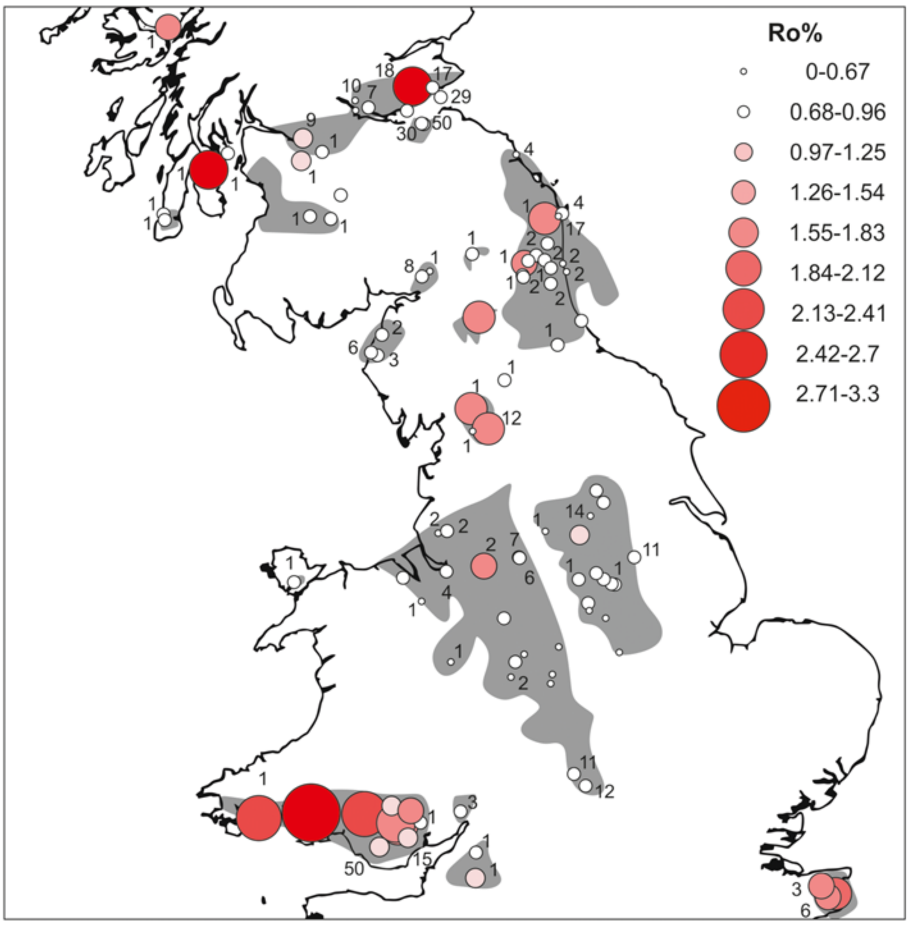

Fig. 4. Vitrinite reflectance (R_0 %) map of Great Britain with R_0 values delimited by spot size. Numbers in map correspond to amount of samples analysed per locality (where information is available). Exposed British coalfields (grey) also shown.

Table 1. *Vitrinite reflectance data for localities and coalfields across Great Britain*

ID	Locality	Coalfield	Lat.	Long.	R_0	*n*	Sample site	Inferred Fm	Depth	Source
1	Inninmore Bay	Morvern	56°31’40.20″N	5°40’17.61"W	0.66	1	Mine seam/spoil	CM	n.g.	This study
2	East Trodigal	Machrihanish	55°25’25.43"N	5°42’49.32"W	0.43	1	Mine seam/spoil	CM	*c.* 300–400 m	This study
3	High Tirfergus	Machrihanish	55°24’08.64"N	5°42’19.35"W	0.38	1	Mine seam/spoil	CM	*c.* 300–400 m	This study
4	Longannet	Fifeshire	56° 3’16.75"N	3°41’51.46"W	0.56	n.g.	Mine seam/spoil	LCF	*c.* 400 m	BCURA (2002, appendix 25A)
5	East Fife	Fifeshire	56°10’25.01"N	3° 1’32.80"W	0.70	17	Onshore outcrop	CM	*c.* 210–360 m	Raymond & Murchison (1991); Marshall *et al.* (1994)
6	Westfield	Fifeshire	56°10’17.57"N	3°17’36.48"W	0.38	10	Mine seam/spoil	CM	*c.* 200 m	Asuen & Onyeobi (2013)
7	Righead	Fifeshire	56° 4’20.46"N	3°38’41.63"W	0.75	7	Borehole	LCG, CM, CG	*c.* 911 m	Raymond & Murchison (1991)
8	Musselburgh	East Lothian	55°56’57.60"N	3° 1’49.62"W	0.80	30	Borehole	LCG, CM	*c.* 800 m	Raymond & Murchison (1991)
9	Eskmouth	East Lothian	55°56’54.23"N	3° 1’39.20"W	0.77	50	Borehole	LCM, MCM, LCF	*c.* 1000 m	Vincent & Rowley (2004)
10	Firth of Forth	Midlothian	56° 9’8.69"N	2°58’17.86"W	0.76	29	Borehole	LCG, CM	*c.* 544–963 m	Raymond & Murchison (1991)
11	Gartlove	Midlothian	56° 6’39.59"N	3°42’33.05"W	0.65	10	Borehole	LCG, CM, CG	*c.* 404–457 m	Raymond & Murchison (1991)
12	Tower 1	Midlothian	56° 4’27.75"N	3° 8’52.84"W	0.82	9	Borehole	LCM, MCM, LCF	*c.* 900 m	Vincent & Rowley (2004)
13	Milton of Balgonie	Midlothian	56°11’44.81"N	3° 7’19.83"W	2.90	18	Borehole	LCM, MCM, LCF	*c.* 700 m	Vincent & Rowley (2004)
14	Watson Head	Lanarkshire	55°34’55.22"N	3°50’51.27"W	0.55	n.g.	Mine seam/spoil	CG, CM	*c.* 650–800 m	Durucan *et al.* (2009)
15	Blackrig	Lanarkshire	55°46’23.21"N	4°16’15.94"W	0.70	1	Onshore outcrop	CG, CM	*c.* 100 m	Cloke *et al.* (1997)
16	Cawdor Cuilt	Lanarkshire	55°54’29.58"N	4°17’41.80"W	0.75	9	Borehole	LCG, CM, CG	*c.* 2–306 m	Raymond & Murchison (1991)
17	Uddingston	Lanarkshire	55°49’19.95"N	4° 6’59.33"W	0.53	1	Mine seam/spoil	CG, CM	n.g.	This study
18	New Cumnock	Ayrshire	55°23’38.18"N	4°12’22.25"W	0.60	n.g.	Mine seam/spoil	CM	*c.* 10–280 m	D. Richardson (pers. comms.)
19	Arran	Ayrshire	55°42’29.00"N	5°13’51.87"W	2.73	1	Mine seam/spoil	CM	*c.* 90 m	This study
20	Ascog, Bute	Ayrshire	55°48’44.12"N	5° 1’21.32"W	0.78	1	Mine seam/spoil	CM	n.g.	This study
21	Kello Water	Ayrshire	55°22’36.32"N	3°59’24.09"W	0.57	1	Mine seam/spoil	CM	*c.* 20 m	This study
22	Ingleton	Ingleton	54°17’2.81"N	2°30’30.25"W	1.57	1	Mine seam/spoil	YG	*c.* 70 m	Shelley (1967)
23	Jenkin Beck	Ingleton	54°08’37.46"N	2°29’17.85"W	0.4	1	Mine seam/spoil	YG	*c.* 40–90 m	This study
24	Alston	Pennines	54°49’44.27"N	2°25’1.87"W	1.60	200+	Onshore outcrop	YG	Highly variable	Creaney (1980)
25	Plashetts	Pennines	55°11’59.74"N	2°29’37.69"W	0.69	1	Onshore outcrop	YG	*c.* 34–40 m	Burnett (1987)
26	Selside	Pennines	54° 9’6.58"N	2°19’28.94"W	1.78	12	Borehole	YG	*c.* 100–300 m	Creaney (1982)
27	Tan Hill	Pennines	54°27’20.08"N	2°09’42.91"W	0.84	1	Mine seam/spoil	YG	*c.* 20–73 m	This study
28	Rowlands Gill	Northumberland	54°59’45.21"N	1°45’15.84"W	1.26	1	Provided by BGS	CM	*c.* 50–95 m	Armstroff (2004)
29	Berwick	Northumberland	55°44’29.42"N	2° 2’33.58"W	0.50	4	Onshore outcrop	YG	n.g.	Burnett (1987)
30	Ellington	Northumberland	55°12’24.45"N	1°41’55.73"W	0.69	n.g.	Mine seam/spoil	CM	*c.* 130 m	BCURA (2002, appendix 20A)
31	Bates	Northumberland	55° 9’7.84"N	1°32’15.56"W	0.67	2	Mine seam/spoil	CM	*c.* 225 m	Asuen & Onyeobi (2013)
32	Crofton Millpit	Northumberland	55° 6’13.35"N	1°30’14.38"W	0.65	2	Mine seam/spoil	CM	*c.* 170 m	Asuen & Onyeobi (2013)
33	East Walbottle	Northumberland	55° 3’23.65"N	1°41’3.50"W	0.69	2	Mine seam/spoil	CM	*c.* 120 m	Asuen & Onyeobi (2013)
34	Weetslade	Northumberland	55° 2’49.09"N	1°36’5.30"W	0.72	2	Mine seam/spoil	CM	*c.* 350 m	Asuen & Onyeobi (2013)
35	North Walbottle	Northumberland	55° 0’26.76"N	1°43’7.39"W	0.73	2	Mine seam/spoil	CM	*c.* 120 m	Asuen & Onyeobi (2013)
36	Rising Sun	Northumberland	55° 0’41.19"N	1°32’1.10"W	0.80	2	Mine seam/spoil	CM	*c.* 235 m	Asuen & Onyeobi (2013)
37	Howick	Northumberland	55°27’0.42"N	1°35’30.57"W	0.81	4	Mine seam/spoil	CM	n.g.	Asuen & Onyeobi (2013)
38	Littlehaughton	Northumberland	55°26’33.25"N	1°36’7.37"W	0.65	17	Mine seam/spoil	CM	n.g.	Asuen & Onyeobi (2013)
39	Alnwick	Northumberland	55°24’56.47"N	1°44’30.57"W	1.61	1	Onshore outcrop	YG	n.g.	Burnett (1987)
40	Throckley	Northumberland	54°56’10.42"N	1°46’59.62"W	0.88	1	Provided by BGS	CM	*c.* 120–260 m	Armstroff (2004)
41	Seaham	Durham	54°48’53.16"N	1°19’36.97"W	0.71	n.g.	Mine seam/spoil	CM	*c.* 400 m	BCURA (2002, appendix 11A)
42	Greenside	Durham	54°55’40.84"N	1°46’50.11"W	0.81	2	Mine seam/spoil	CM	*c.* 50–150 m	Asuen & Onyeobi (2013)
43	Leasingthorne	Durham	54°40’1.03"N	1°36’35.89"W	0.84	1	Onshore outcrop	CG, CM	*c.* 125 m	Cloke *et al.* (1997)

(continued)

Table 1. (Continued)

ID	Locality	Coalfield	Lat.	Long.	R_0	*n*	Sample site	Inferred Fm	Depth	Source
44	Washington	Durham	54°54’39.36"N	1°31’43.12"W	0.90	2	Mine seam/spoil	CM	*c.* 220 m	Asuen & Onyeobi (2013)
45	Canonbie	Canonbie	55° 3’51.64"N	3° 1’24.94"W	0.84	8	Borehole	CM	*c.* 200–800 m	New Age Exploration (2014)
46	Rowanburn	Canonbie	55°05’08.45"N	2°55’49.88"W	0.58	1	Mine seam/spoil	CM	n.g.	This study
47	Keekle	Cumberland	54°34’52.49"N	3°29’25.68"W	0.85	3	Provided by BGS	CM	*c.* 32–64 m	Armstroff (2004)
48	Potato Pot	Cumberland	54°35’35.81"N	3°29’56.40"W	0.81	3	Provided by BGS	CM	*c.* 25–78 m	Armstroff (2004)
49	Distington	Cumberland	54°35’51.47"N	3°32’12.55"W	0.74	6	Provided by BGS	CM	*c.* 12–110 m	Armstroff (2004)
50	Dearham	Cumberland	54°42’18.40"N	3°27’3.23"W	0.78	2	Provided by BGS	CM	*c.* 44–56 m	Armstroff (2004)
51	Kellingley	Yorkshire	53°42’28.55"N	1° 7’40.95"W	0.68	n.g.	Mine seam/spoil	CM	*c.* 525 m	BCURA (2002, appendix 13A)
52	Cortonwood	Yorkshire	53°30’13.94"N	1°22’41.21"W	1.03	n.g.	Mine seam/spoil	CM	*c.* 525 m	BCURA (2002, appendix 7A)
53	Gascoigne Wood	Yorkshire	53°46’48.89"N	1°12’12.24"W	0.72	n.g.	Mine seam/spoil	CM	*c.* 400 m	BCURA (2002, appendix 16A)
54	Markham Main	Yorkshire	53°32’32.08"N	1° 4’4.57"W	0.50	n.g.	Mine seam/spoil	CM	*c.* 400 m	BCURA (2002, appendix 29A)
55	Hepworth	Yorkshire	53°33’23.84"N	1°45’6.40"W	0.60	1	Mine seam/spoil	CM	*c.* 11–22 m	Pearson & Russell (2000)
56	Kirk Smeaton	Yorkshire	53°37’36.48"N	1°13’37.75"W	0.65	14	Borehole	CM	*c.* 10–900 m	Andrews (2013)
57	Calow	Derbyshire	53°13’57.90"N	1°23’11.13"W	0.88	1	Borehole	CM	*c.* 186–342 m	Pearson & Russell (2000)
58	Creswell	Derbyshire	53°16’1.29"N	1°12’26.89"W	0.86	n.g.	Mine seam/spoil	CM	*c.* 30 m	BCURA (2002, appendix 9A)
59	Nadins	Derbyshire	52°47’35.86"N	1°34’15.86"W	0.44	n.g.	Mine seam/spoil	CM	*c.* 0–46 m	BCURA (2002, appendix 35A)
60	Lower House 1	Derbyshire	53°22’6.49"N	2°0’43.85"W	0.63	7	Borehole	CM	*c.* 150 m	DECC (2013)
61	Lower House 2	Derbyshire	53°22’6.49"N	2°0’43.85"W	0.70	6	Borehole	CM	*c.* 150–250 m	DECC (2013)
62	Gainsborough	Nottinghamshire	53°22’1.69"N	0°48’13.59"W	0.73	11	Borehole	CM	*c.* 762–1401 m	Pearson & Russell (2000)
63	Bentinck	Nottinghamshire	53°4’54.27"N	1°17’9.93"W	0.67	n.g.	Mine seam/spoil	CM	*c.* 112 m	BCURA (2002, appendix 23A)
64	Thoresby	Nottinghamshire	53°12’2.51"N	1°2’38.32"W	0.70	n.g.	Mine seam/spoil	CM	*c.* 440 m	BCURA (2002, appendix 12A/18A)
65	Welbeck	Nottinghamshire	53°13’55.23"N	1°7’31.38"W	0.74	1	Onshore outcrop	CM	Up to 634 m	Cloke *et al.* (1997)
66	Ollerton	Nottinghamshire	53°11’57.05"N	1°0’59.91"W	0.68	n.g.	Mine seam/spoil	CM	*c.* 440 m	BCURA (2002, appendix 22A)
67	Annesley	Nottinghamshire	53°4’44.92"N	1°17’4.37"W	0.71	n.g.	Mine seam/spoil	CM	*c.* 112 m	BCURA (2002, appendix 21A)
68	Tupton	Nottinghamshire	53°1’15.75"N	1°16’36.26"W	0.49	n.g.	Mine seam/spoil	CM	*c.* 25–90 m	Durucan *et al.* (2009)
69	Gedling	Nottinghamshire	52°58’52.59"N	1°4’9.09"W	0.54	n.g.	Mine seam/spoil	CM	*c.* 270 m	BCURA (2002, appendix 30A)
70	Up Holland	Lancashire	53°32’14.99"N	2°44’15.77"W	0.83	2	Borehole	CM	*c.* 45–292 m	Pearson & Russell (2000)
71	Skelmersdale	Lancashire	53°32’22.33"N	2°48’3.96"W	0.58	2	Borehole	CM	*c.* 520–1554 m	Pearson & Russell (2000)
72	Knutsford	Cheshire	53°18’44.51"N	2°22’29.04"W	1.30	2	Borehole	CM	*c.* 2890–3045 m	Pearson & Russell (2000)
73	Ince Marshes	Cheshire	53°17’12.11"N	2°46’15.46"W	0.70	4	Borehole	CM	*c.* 0–500 m	Andrews (2013)
74	Point of Ayr	North Wales	53°14’22.10"N	3°12’55.45"W	0.72	n.g.	Mine seam/spoil	CM	*c.* 197 m	BCURA (2002, appendix 8A)
75	Anglesey	North Wales	53°12’9.11"N	4°20’48.59"W	0.71	1	Onshore outcrop	CM	*c.* 40 m	Duncan *et al.* (1998)
76	Wrexham	North Wales	53°04’23.37"N	3°3’13.41"W	0.65	1	Onshore outcrop	CM	n.g.	This study
77	Lea Hall	Staffordshire	52°45’32.57"N	1°55’23.11"W	0.56	n.g.	Mine seam/spoil	CM	*c.* 396 m	BCURA (2002, appendix 32A)
78	Hem Heath	Staffordshire	52°59’10.17"N	2°10’3.74"W	0.76	n.g.	Mine seam/spoil	CM	*c.* 345 m	BCURA (2002, appendix 14A)
79	Littleton	Staffordshire	52°42’38.59"N	2°2’44.28"W	0.72	n.g.	Mine seam/spoil	CM	*c.* 183 m	BCURA (2002, appendix 27A)
80	Baggeridge	Staffordshire	52°32’15.22"N	2°8’40.44"W	0.55	2	Borehole	CM	*c.* 620 m	DECC (2013)
81	Hanwood	Shropshire	52°40’45.65"N	2°50’08.37"W	0.52	1	Onshore outcrop	CM	*c.* 142–275 m	This study
82	Asfordby	Leicestershire	52°46’29.57"N	0°56’25.22"W	0.48	n.g.	Mine seam/spoil	CM	*c.* 460 m	BCURA (2002, appendix 28A)
83	Daw Mill	Warwickshire	52°30’33.06"N	1°37’8.46"W	0.60	n.g.	Mine seam/spoil	CM	*c.* 500 m	BCURA (2002, appendix 31A)
84	Baddesley	Warwickshire	52°35’7.26"N	1°35’44.24"W	0.55	n.g.	Mine seam/spoil	WG, CM	*c.* 420 m	BCURA (2002, appendix 34A)
85	Steeple Aston	Oxfordshire	51°55’25.68"N	1°19’0.75"W	0.70	12	Borehole	WG, CM	*c.* 300–400 m	DECC (2013)
86	Withycombe	Oxfordshire	51°59’58.32"N	1°26’8.86"W	0.68	11	Borehole	CM	*c.* 500–850 m	DECC (2013)
87	Forest of Dean	Forest of Dean	51°45’27.63"N	2°36’59.42"W	0.80	3	Borehole	CM	*c.* 50–220 m	DECC (2013)

88	Wyllie	South Wales	51°36′37.36″N	3°11′31.40″W	1.14	15	Mine seam/spoil	CM	*c.* 190 m	Gayer & Fowler (1997)
89	Llanilid	South Wales	51°31′31.79″N	3°27′36.66″W	1.07	50	Mine seam/spoil	CM	n.g.	Gayer & Fowler (1997)
90	Tower	South Wales	51°44′27.95″N	3°36′52.84″W	2.28	n.g	Mine seam/spoil	CM	*c.* 165 m	Durucan *et al.* (2009)
91	Selar	South Wales	51°44′16.87″N	3°37′23.20″W	2.41	n.g	Mine seam/spoil	CM	n.g.	Durucan *et al.* (2009)
92	Cwmbargoed	South Wales	51°44′20.62″N	3°19′40.60″W	1.06	n.g	Mine seam/spoil	CM	*c.* 650 m	BCURA (2002, appendix 6A)
93	Cynheidre	South Wales	51°44′46.37″N	4°10′31.10″W	3.29	n.g	Mine seam/spoil	CM	*c.* 250 m	BCURA (2002, appendix 1A)
94	Taff Merthyr	South Wales	51°41′14.97″N	3°16′55.54″W	1.87	n.g	Mine seam/spoil	CM	*c.* 192 m	BCURA (2002, appendix 2A)
95	Deep Navigation	South Wales	51°39′32.15″N	3°15′51.73″W	1.98	n.g	Mine seam/spoil	CM	*c.* 650 m	BCURA (2002, appendix 4A)
96	Cwm	South Wales	51°45′36.82″N	3°11′2.04″W	1.37	n.g	Mine seam/spoil	CM	*c.* 686 m	BCURA (2002, appendix 5A)
97	Hafodyrynys	South Wales	51°40′54.82″N	3°5′53.07″W	0.86	1	Mine seam/spoil	CM	*c.* 25 m	Smith (1996)
98	Pembroke	South Wales	51°42′35.44″N	4°41′37.32″W	2.13	1	Mine seam/spoil	CM	*c.* 146–183 m	This study
99	Cattybrook	Bristol	51°29′21.28″N	2°27′28.18″W	0.87	1	Onshore outcrop	CM	*c.* 22–27 m	Smith (1996)
100	Midsomer Norton	Bristol	51°17′44.77″N	2°29′51.45″W	1.06	1	Mine seam/spoil	CM	*c.* 184–502 m	This study
101	Tilmanstone	Kent	51°12′34.99″N	1°16′17.26″E	1.55	n.g	Mine seam/spoil	WG, CM	*c.* 650 m	BCURA (2002, appendix 3A)
102	Barfreston	Kent	51°12′0.99″N	1°14′1.94″E	1.35	6	Borehole	WG, CM	*c.* 400–800 m	DECC (2013)
103	Snowdown	Kent	51°12′54.83″N	1°12′55.32″E	1.30	3	Borehole	WG, CM	*c.* 450–700 m	DECC (2013)

Lat., latitude; Long., longitude; R_0, mean vitrinite reflectance; *n*, number of analyses; Inferred Fm, inferred host formation; CM, Coal Measures (Upper, Middle, Lower); WG, Warwickshire Group; CG, Clackmannan Group; LCG, Limestone Coal Group; LCF, Lower Limestone Formation; YG, Yoredale Group; n.g., number of analyses not given or not deciphered from source. Depths given estimated based on seam stratigraphy, shaft excavation depth or borehole data (where available).

were expelled northwards, causing mineralization in South Wales, and contributing to the maturation of coal (Gayer *et al.* 1997; Alderton *et al.* 2004). The Variscan thrust system propagated northwards into the coalfield even as Pennsylvanian sedimentation was continuing (Gayer *et al.* 1998). The pattern of elevated reflectance in coals adjacent to the orogenic front extends west across Ireland (Clayton *et al.* 1989) and east in continental Europe (Koch 1997). In the north of England, coals on the Alston Block were subject to anomalous heat flow from the Devonian Weardale Granite (Creaney 1980; Manning *et al.* 2007). There is a marked change in reflectance over just a few kilometres from high values in the Pennines to low values in the Ingleton Coalfield, across the Craven Faults. The coal on Arran was metamorphosed by the intrusion of Paleogene granite (Fyfe *et al.* 1993). Contact metamorphism associated with laterally extensive Tertiary basaltic dykes may have also affected coals across Ayrshire (southern Scotland), Cleveland (north Yorkshire), Anglesey (north Wales) and central England.

The data imply that the potential for definitive discrimination of source regions in provenance studies is limited. Coals from along the Variscan orogenic front can be identified, and a regional distinction can be made between northern England and regions to the north and south. Consequently, where reflectance has been used for provenance in archaeological studies (Smith 1996, 2005; Erskine *et al.* 2008), the results are confirmatory rather than definitive.

Contact metamorphism can play a pivotal role in organic matter thermal maturity (Bishop & Abbott 1993, 1995). Some coals may have experienced short-term additional heating. For example, samples from Bute and Fife exhibit veining by calcite owing to hydrothermal activity. However, reflectance is a kinetically controlled parameter, and so is influenced by long-term heat flow rather than short-term events, as observed elsewhere (Parnell *et al.* 2005).

Conclusions

The reported database is the first comprehensive collation of vitrinite reflectance for British coals. In addition to providing a frame of reference for thermal maturity in sedimentary sections of Carboniferous age, the database of vitrinite reflectance has applications for diverse purposes that involve national surveys. For example, the data can be used in assessments of coal bed methane (DECC 2013), shale gas potential (Smith *et al.* 2011), geothermal energy (Gluyas *et al.* 2018) and the interpretation of trace element data in coals (Bullock *et al.* 2018).

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