Modelled hot sedimentary aquifer geothermal potential of Upper Devonian strata in the Midland Valley of Scotland

Decarbonisation and Resource Management Programme

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BRITISH GEOLOGICAL SURVEY

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Keywords

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Front cover

Upper Devonian sandstones at the Bunnet Stane, Fife. P638501 M Browne BGS©UKRI.

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This report builds on the significant work of the 1980's geothermal programme and the contributions of many former BGS colleagues and university collaborators; references are listed in the text. It also draws on years of data digitisation and compilation of borehole, well, seismic and mining information that constrain subsurface geological models of the Midland Valley of Scotland. Particularly we wish to note the work of former colleagues Tony Irving, Bill McLean, Martyn Quinn, Don Cameron and Mike Browne.

This work has used SKUA-GOCAD™ v22 software provided under academic licence and the open source 3DHIP software developed by Piris et al. (2021) for the assessment of deep geothermal resources.

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Summary

A regional-scale estimate of the Heat-In-Place for the 'hot sedimentary aquifer' (or 'hydrothermal') potential geothermal energy source in the sandstone-dominated strata of central Scotland has been conducted for the first time. This report describes the lithology and rock properties of the target units now classified as Upper Devonian in age – the Kinnesswood Formation and Stratheden Group – the construction of an updated 3D geological model of depth and thickness, as well as values and assumptions used for the potential geothermal energy source estimation.

The modelled distribution and estimation of the potential resource are provided with high uncertainty due to the data quantity and quality for the Kinnesswood Formation and Stratheden Group target, where buried at several kilometres depth. Uncertainties range from the presence and thickness of the units to their porosity, permeability and temperature.

This estimation represents a starting point for more detailed analysis and interpretations, highlighting potential opportunities from 44-166°C at depths of up to 6 km. Ultimately, deep geothermal wells need to be drilled to de-risk the target. The resource potential for direct heat utilisation is assessed using an upper 1.4 km depth cut-off relative to Ordnance Datum, at which the average of the collected temperature data approximates to 50°C. Using the statistical approach of the heat calculator of Piris et al. (2021), the modelled results are P10 = 361.1 EJ, P50 = 341.7 EJ, P90 = 312.5 EJ for the modelled Heat-In-Place and tentatively P10 = 51.4 GW, P50 = 35.6 GW, P90 = 23.2 GW for the modelled recoverable heat. The values are decreased by approximately a third by removing areas further than 1 km offshore in the Firth of Forth, for which the heat demand and techno-economics would be significantly different. Resultant Heat-In-Place values for onshore and within 1 km of the coastline are P10 = 257.8 EJ, P50 = 243.9 EJ and P90 = 223.1 EJ, and P10 = 36.7 GW, P50 = 25.4 GW and P90 = 16.6 GW for modelled recoverable heat.

After establishing the presence and thickness of the target geothermal reservoir, the achievable and sustainable flow rate is a key parameter for a potential hot sedimentary aquifer estimation. Aquifer properties of the Kinnesswood Formation and Stratheden Group target vary from 0–31.2% and 0.004–2212 mD close to surface and in the Glenrothes borehole at 428 m, through intergranular and fault/fracture flow. The variability represents different beds and spatial locations highlighting the heterogeneity of the target aquifer/reservoir. The Knox Pulpit Formation and lateral equivalents are believed to be the most homogenous. A key uncertainty to the geothermal potential across the Midland Valley of Scotland remains whether the aquifer properties deteriorate at depths greater than 500 m.

Despite the high geological uncertainty, the hot sedimentary aquifer presents significant opportunity for a decentralised heat supply in central Scotland, coincident with some major population centres including Stirling, Glasgow, Falkirk and Dunfermline. Compared to other UK geothermal opportunities (e.g. Permo-Triassic sandstones: 8 EJ Worcester Basin, 122 EJ Eastern England in Abesser et al. 2023) the Heat-In-Place values are large due to the greater depth and unit thickness combined with moderate porosity values, though the geological uncertainty is higher.

Sandstone-dominated units of Strathmore basin (Lower Devonian), Moray and Caithness basins (Devonian), the Borders (Upper Devonian) and Dumfries and Galloway (Permian) forming moderate, high and very high productivity aquifer units at outcrop and shallow subsurface across Scotland form potential aquifer geothermal opportunities. They have not been assessed during this study due to lack of subsurface data. The Passage Formation high productivity aquifer (Carboniferous) was included in this model and assessment but with maximum burial depths of around 1 km onshore (corresponding to maximum estimated temperatures of around 34°C), this unit will be considered further in a separate analysis of the shallower, lower temperature geothermal energy source for open loop ground source heat systems, along with the shallower parts of the Upper Devonian strata modelled here.

1 Introduction

With increasing drive to decarbonise heating in the UK and globally to meet Net Zero targets, as well as to increase energy security, there is growing Government and industry interest in geothermal resources (e.g. HM Government 2021, 2022; Scottish Government, 2021). This includes in areas of the Earth's crust with relatively low geothermal gradients, such as the UK. The low enthalpy resources available in sedimentary basins providing temperatures up to 100°C at depths up to 4–5 km are one such opportunity, commonly termed 'hot sedimentary aquifers' or 'hydrothermal' (Downing and Gray, 1986; Busby, 2014; Abesser and Walker, 2022; Abesser et al. 2023).

Whilst assessments of Heat-In-Place geothermal potential have been made for other UK basins (e.g. Rollin et al. (1995), Pasqualli (2010), Jackson (2012), Busby (2014), Sutton (2022), Jones et al. (2023), summary in Abesser et al., 2023), such an estimation has not been published for sedimentary basins in Scotland.

This study focuses on improving understanding of the modelled Heat-In-Place and tentative recoverable geothermal heat energy estimation within the sedimentary basins of the onshore* Midland Valley of Scotland. The main focus was on interpretation of aquifer units buried beneath 1.4 km relative to Ordnance Datum and modelled to reach temperatures of greater than *c.*50°C, that may form a geothermal resource for direct use heat applications. Mapping of lower temperature resources that may be considered for open loop ground source heat pump systems or mid depth temperature aquifer thermal energy storage (ATES) systems will be covered in a future report.

(*onshore also includes the Firth of Forth estuary, following the convention of petroleum licence blocks)

1.1 OVERVIEW OF GEOLOGY OF THE MIDLAND VALLEY OF SCOTLAND

The Midland Valley of Scotland (MVS) comprises a series of Devono-Carboniferous basins situated between the Highland Boundary and Southern Upland faults. Across central Scotland from Ayr to Glasgow, Edinburgh and Fife, the Upper Devonian and Carboniferous basins contain up to 5–6 km of sedimentary and volcanic rock sequences. Deposited in dominantly fluvial, fluvio-deltaic and shallow marine settings, sandstones form variable-quality aquifer (reservoir) units. Where laterally continuous, thick, and buried to suitable depths, these sandstones form potential geothermal targets (section 2.1). As a result of a complex structural evolution, there are variations in the extent, depth and thickness of these stratigraphical units across NNE- and NE-trending anticlines and synclines and E-, NE- and NW- trending faults. Recent geological summaries are given in Marshall (2024) and Monaghan et al. (2024).

1.2 PREVIOUS GEOTHERMAL RESEARCH

A comprehensive assessment of the deep geothermal potential of the Midland Valley of Scotland was included within the 1980's geothermal programme (Browne et al. 1985; Downing and Gray 1986; Browne et al. 1987; Brereton et al. 1988). The main geothermal targets identified were the Kinnesswood Formation (assigned to the Carboniferous, subsequently re-assigned to the Upper Devonian) and the Knox Pulpit Formation, part of the Upper Devonian Stratheden Group. The Knox Pulpit Formation exhibited the best aquifer properties with porosity up to 20%, though with probable low primary and secondary fracture permeability where buried at depth (Downing and Gray 1986; Brereton et al. 1988). In the Fife, Falkirk and Glasgow areas, it was speculated that temperatures of 40–75°C could be achieved where these strata were buried at depth (Downing and Gray 1986; Browne et al. 1987; Brereton et al. 1988).

The programme included the drilling of the 567 m deep Glenrothes borehole (NS20 SE 385 [325615, 703142]; (Browne et al. 1986; Brereton et al. 1988)). Though terminating at relatively shallow depth in the condensed section of the footwall block of the East Ochil Fault, the Glenrothes borehole remains the only borehole drilled in Scotland specifically for the purpose of evaluating a deep geothermal 'hydrothermal' or 'hot sedimentary aquifer' target (the Knox Pulpit

Formation) and measuring heat flow. The borehole was mostly cored and geophysically logged. The non-equilibrium bottomhole temperature was 19°C with a calculated heat flow of 56.5 mWm^2 (Brereton et al. 1988).

The 1980's geothermal programme outcome was that the potential for geothermal resources in central Scotland was likely limited by the aquifer properties and flow rates of the target intervals. Whilst Browne et al. (1987) highlighted that a transmissivity of over 20 Dm was calculated for the Glenrothes borehole (the cut off used in Downing and Gray, 1986); the economics (at that time competing against cheap natural gas) and geological uncertainties resulted in the work not progressing. The 'accessible resource base' of the Midland Valley of Scotland was not calculated at that time. The Passage Formation was also considered as a shallower potential target, with temperatures between 10–40°C (Browne et al. 1987).

Subsequently, boreholes/wells and studies for oil and gas, coal, coal bed methane, shale gas, carbon capture and storage (CCS) and regional geophysical studies have provided additional deep subsurface data, subsurface models and geological understanding (Rollin 1995; Underhill et al. 2009; Monaghan et al. 2012; Monaghan, 2014a). Additional data points on temperature and lithostratigraphy are now accessible from late 1980's–2010's oil and gas and coal bed methane wells, with corresponding porosity, mineralogical and petrological studies (Milodowski and Ruston, 2009; Monaghan et al. 2012; also see below).

More recently, a number of studies have focussed on aspects of the deep geothermal potential of central Scotland:

- Gillespie et al. (2013) provided an overview of sedimentary basins and aquifer rocks in Scotland, as well as hypothesizing that there may be thermal anomalies beneath igneous rock sequences at offshore basin margins.
- Comerford et al. (2018) developed fault, fracture and permeability modelling including the Stratheden Group for geothermal heat recovery at Guardbridge, near St Andrews.
- Heinemann et al. (2018) considered at high level various geoenergy uses in the MVS, including deep geothermal targets of central Scotland.
- Three research theses: Watson (2022) estimated the depth of the Stratheden Group beneath eastern Glasgow, analysed heat flow and rock properties; Williams (2022) examined the depth, temperatures and rock properties of the Stratheden Group around the Clackmannan Syncline; Shepherd (2014) used well log and fracture interpretations in analysis of Devono-Carboniferous sandstones.

Different authors have made different interpretations of the limited deep well data, incorporated variable amounts and types of legacy data and hydrogeological datasets resulting in a range of geological models to constrain the geothermal resource. Common themes include the relatively poor porosity and permeability characteristics in the Kinnesswood Formation and Stratheden Group as a whole, the likely deterioration of porosity and permeability at depth, the importance of fracture flow for the deep geothermal resource, coupled with the poor understanding of fracture characteristics at depth.
The datasets, assumptions and limitations of this study are described below.

1.3 CLASSIFICATION

Using the classification scheme of Moeck (2014), the Midland Valley of Scotland, Upper Devonian rocks would be classified as 'CD1' - a hydrothermal potential reservoir within an intracratonic / rift basin that is litho/biofacies controlled and fault/fracture controlled. The current level of understanding is judged to be at the geosystem and play level for 'prospective resources' in the classification of Moeck and Beardsmore, 2014.

Under the UNFC (2019, 2022) classification scheme for resources applied to geothermal energy, the Midland Valley of Scotland, Upper Devonian rocks are judged to be classified as a Potential Source, where "favourable conditions for the potential development in an area may be inferred from regional studies" (F3.3) but are unconfirmed due to limited technical data and because the "environmental-socio-economic viability cannot yet be determined due to insufficient information" (E3.2) with high estimate/low confidence (G4). The possibility of discovery has not currently been estimated.

2 Geology and stratigraphical framework

2.1 GEOTHERMAL POTENTIAL TARGETS AND EXCLUSIONS

The Upper Devonian Kinnesswood Formation and Stratheden Group strata form the main, regionally extensive target for this study (section 2.2; Figure 1) and are predominantly sandstone with subordinate mudstone, pedogenic nodular limestone and conglomerate. At surface these rocks are a shallow productive aquifer units for groundwater supply, and are buried by Carboniferous-Permian strata to over 5 km depth in the centre of sedimentary basins.

The Carboniferous Passage Formation was included the geological modelling and initial analysis. The unit is sandstone dominated and buried to nearly 1 km in the centre of onshore sedimentary basins. However, it is not included in the geothermal potential estimation for direct heat use as temperatures are estimated to reach a maximum of around 34°C onshore and are more appropriate for lower temperature heating, cooling and storage applications, and will be evaluated in a subsequent study.

2.1.1 Exclusions due to data availability

Lower Devonian sandstone and conglomerate strata of Strathmore (e.g. Strathmore and Arbuthnott-Garvock groups) and the southern Midland Valley (e.g. Lanark Group) have moderate-high aquifer productivity, dominated by fracture flow (minor intergranular; Ó Dochartaigh et al. 2015) and were described as a potential deep geothermal target in Gillespie et al. (2013). However, they are not included in this analysis since:

- There is very little or no constraining subsurface data (boreholes, seismic) greater than tens of metres below the surface;
- The aquifer is dominated by fracture flow with data on open fractures to 150 m deep, is known to be very heterogenous, and with indications that fractures seen at surface are closed at depth (Downing and Gray, 1986). At depths greater than 500 m, the aquifer is poorly understood;
- At the surface, the rocks commonly contain an abundant fine-grained matrix or diagenetic cements which occlude porosity (Downing and Gray, 1986);
- Significant uncertainty would exist within any geological model and resultant Heat-In-Place calculation.

Sandstones, fractured limestones, strata within fault damage zones etc. within the heterolithic Carboniferous sequence of the Midland Valley may locally form potential geothermal targets; overall these are classified as moderate aquifer productivity (fracture, minor intergranular) in O Dochartaigh et al. (2015) and some form hydrocarbon reservoirs (Underhill et al. 2009). Spatial/depth variability in rock types (e.g. channelised sandstones) and thickness preclude a regional scale resource estimation at the current time.

2.1.2 Geographical exclusions

There are other potential aquifer/reservoir units onshore Scotland that have not been included within the current study:

- The Mid and Lower Devonian sandstones of Moray and Caithness are considered to have low to high aquifer productivity (fracture, minor intergranular; Ó Dochartaigh et al. 2015) and were not included for the same reasons of data availability as in section 2.1.1 above.
- Units to the south of the Southern Uplands located on the northern margin of the Northumberland-Solway Basin and Tweed Basin have not been considered here, nor have the relatively small and shallow Permo-Trias basins of Ayrshire, Dumfries and Galloway (see Figure 25 in Gillespie et al. 2013)

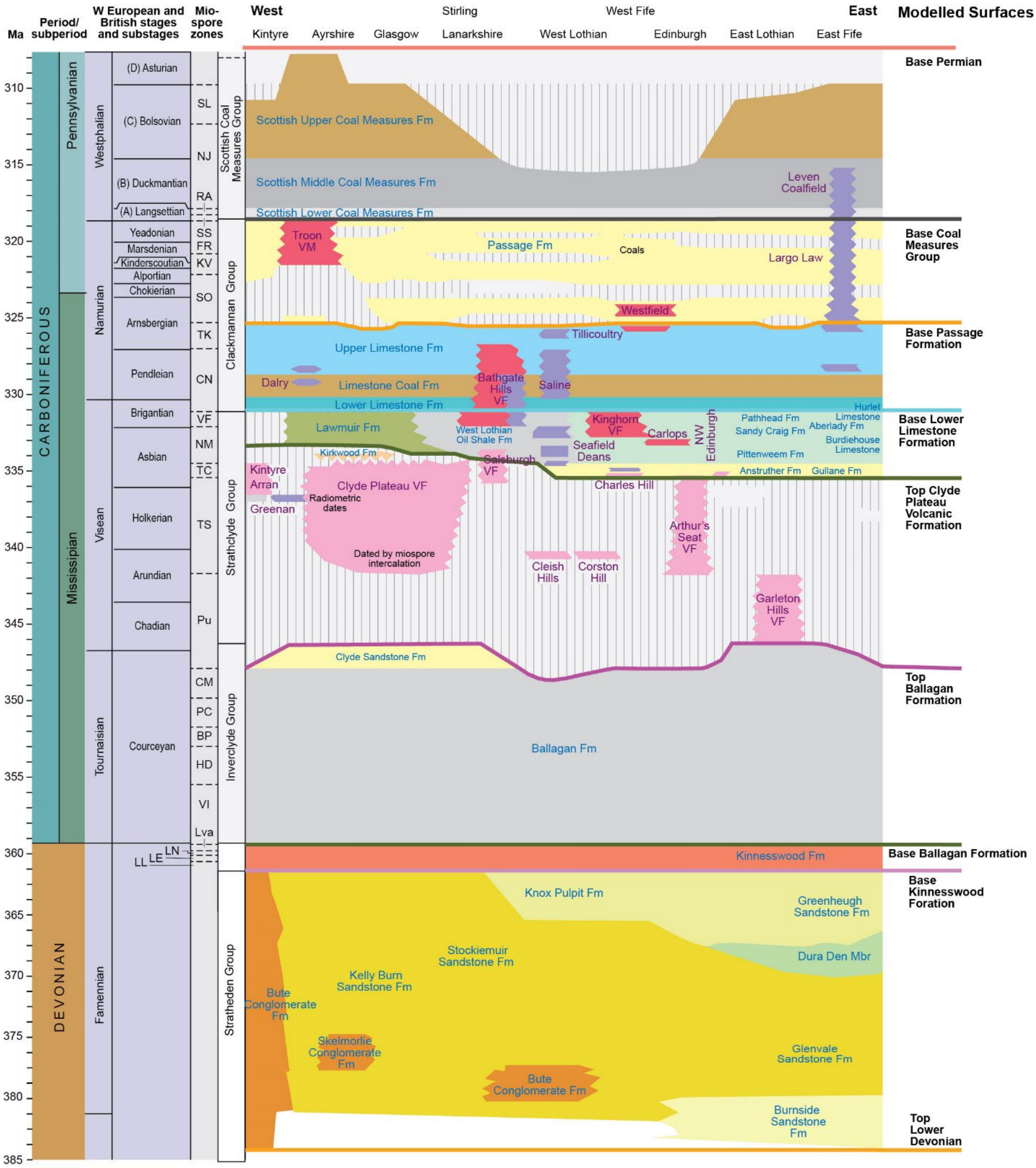

Figure 1 Summary stratigraphy, modified from Monaghan et al. (2024), Marshall (2024), Browne et al. (1999, 2002). The right-hand side summarises the surfaces included in the geological model (Section 3).

2.2 KINNESSWOOD FORMATION AND STRATHEDEN GROUP

Formerly the Kinnesswood Formation was included in the lower Carboniferous, as part of the Inverclyde Group (Browne et al. 1999). However, Marshall et al. (2019) established that the Kinnesswood Formation is of uppermost Devonian age (Figure 1).

The Kinnesswood Formation comprises fine- to coarse-grained sandstones, siltstones and conglomerates deposited in terrestrial fluvial and overbank environments. It is identified based on the presence of calcretes (Marshall et al. 2019). These can take the form of nodular calcrete but can also form 5 m thick continuous beds of calcrete (Wright et al. 1993). Its thickness calculated from surface outcrops is variable, on average around 200 m (up to 640 m in the Edinburgh area). Borehole penetrations show the unit to range from 32-169 m in thickness.

The porosity characteristics are described further in section 4.1 below. The permeability as measured by core analyses were summarised as less than 10 mD in Downing and Gray (1986) and 0.1 to over 400 mD in samples from the Glenrothes borehole (Brereton et al. 1988).

The Stratheden Group comprises formations interpreted to be deposited in fluvial and aeolian environments, with varying proportions of sandstone, conglomerate, siltstone and mudstone. The thickness of the units is variable, for example the combined sequence of the Knox Pulpit, Glenvale Sandstone and Burnside Sandstone formations in Fife may reach 680 m; in the Edinburgh area the unit is absent as boreholes penetrating the Kinnesswood Formation directly overlie Lower Devonian strata (Mitchell and Mykura, 1962). The upper 120 m of the Stockiemuir Sandstone Formation in the Stirling area is also interpreted as partly aeolian in origin and correlative with the Knox Pulpit Formation (Hall and Chisholm, 1987; Browne et al. 2002).

In the Scottish Borders, the Stratheden Group comprises the Greenheugh Sandstone and Redheugh Mudstone formations with a combined thickness of 370 m, resting unconformably on Silurian strata at Siccar Point (Browne et al. 2002).

In central Fife, the Stratheden Group is an important freshwater aquifer (Foster et al. 1976 in Downing and Gray 1986). The c. 170 m thick Knox Pulpit Formation within the Stratheden Group is of particular interest. It comprises fine- to coarse-grained cross-bedded sandstone of possible aeolian origin that is weakly cemented at outcrop. At depths less than 80 m, samples have given porosities of over 20% and permeability greater than 600 mD, with jointing and fissure systems also controlling groundwater flow (Browne et al. 1987; Downing and Gray 1986). Yields of 40 L/s and specific capacities of around 130 m^3/dm are documented. Shallow samples of other formations of the Stratheden Group give porosity values of 10–20% and permeabilities of about 240 mD, but with borehole yields of less than 10 L/s (Downing and Gray, 1986). Petrological examination of samples of the Stratheden Group with lower porosity and permeability values showed carbonate and argillaceous material filling pores, as well as quartz overgrowths and authigenic kaolinite.

In the Glenrothes borehole at measured depths of around 500 m from ground level, the porosity and permeability of the Knox Pulpit Formation was reduced, nevertheless the mean horizontal permeability of 85 mD and overlying and underlying formations were judged to provide a transmissivity of over 20 Dm (Browne et al. 1987).

Samples of the Upper Devonian strata from Ayrshire to 100 m depth gave lower porosity values of 3–22% and 10–47 mD, though 90% of groundwater movement is believed to be by fissure flow (Downing and Gray 1986).

2.3 CAVEATS AND LIMITATIONS TO THE GEOLOGICAL INTERPRETATION

The deep regional structure, stratigraphy, rock, temperature and aquifer properties of the Midland Valley is relatively well understood to the base of the Clackmannan Group (Lower Limestone Formation) and top parts of the Strathclyde Group by boreholes/wells, seismic data, coal and other mine plan information (e.g. Monaghan et al. 2012; Monaghan 2013; Monaghan 2014b). This information is included within the geological model presented here. Lower parts of the Strathclyde Group, volcanic rocks, the Inverclyde Group and Upper Devonian strata are much more poorly constrained by subsurface data, being limited to a handful of boreholes/wells, poor quality of seismic data and limited measurements of rock, aquifer properties and temperatures (Figure 2). This limitation of a lack of controlling data results in high uncertainty on the geological model for the Upper Devonian target units considered here and in key parameters for the Heat-In-Place calculations (thickness; temperature, porosity; Sections 4 and 5).

Appendix 1 summarises uncertainties and limitations in the borehole/well interpretations and in the constraints on the extent and thickness of the target units. Of particular note are that

- the geological model and Heat-In-Place estimation presented does not match the deepest well interpretation of the Stratheden Group. This is because the Inch of Ferryton well is interpreted on seismic to pass through a fault into a fault footwall; however, the fault is too small to be included within the regional model grid;

- the poorly constrained and variable extent and thickness of lower Carboniferous volcanic units and target units

3 Geological modelling (geological depth surfaces and faults)

The regional 3D geological model covers the Midland Valley with the corner extents being approximately SW 220000, 599000 to NE 370000, 720000. The model extends to a depth of -5 km below sea level.

The purpose of the model was to undertake a regional assessment of the potential geothermal target, particularly for the deeply buried Upper Devonian strata. The model is applicable for use at scales between 1:100,000 and 1:500,000 and is not suitable for city or site scale assessments.

3.1 INPUT DATA

The 3D geological model was created using borehole/well horizon markers, depth converted seismic picks and polygons defining the erosional limits of formations at outcrop from BGS surface mapping. Most of the bases of the modelled units incorporated surfaces from previous models (Table 1). The fault network was derived from Monaghan (2013) and included only the largest faults in the region, commonly those with lengths greater than 20 km and throws greater than 2 km.

In total, 478 boreholes/wells were used in the model area. Of these 124 intersected the base of the Passage Formation; 8 intersected the top of the Kinnesswood Formation; 6 intersected the base of the Kinnesswood Formation (the majority being shallow and starting where this unit was at surface) and 2 deep wells are interpreted to penetrate to Lower Devonian in study area. The stratigraphic interpretations were re-downloaded from the BGS Borehole Geology database, choosing the interpreter codes ‘AAMI’ and then ‘TMCM’. For the boreholes that intersected the Upper Devonian strata each borehole was inspected, and multiple interpretations were compared and rationalised including Browne et al (1987); Monaghan (2014b, appendix C); Heinemann et al. (2018) (Appendix 1).

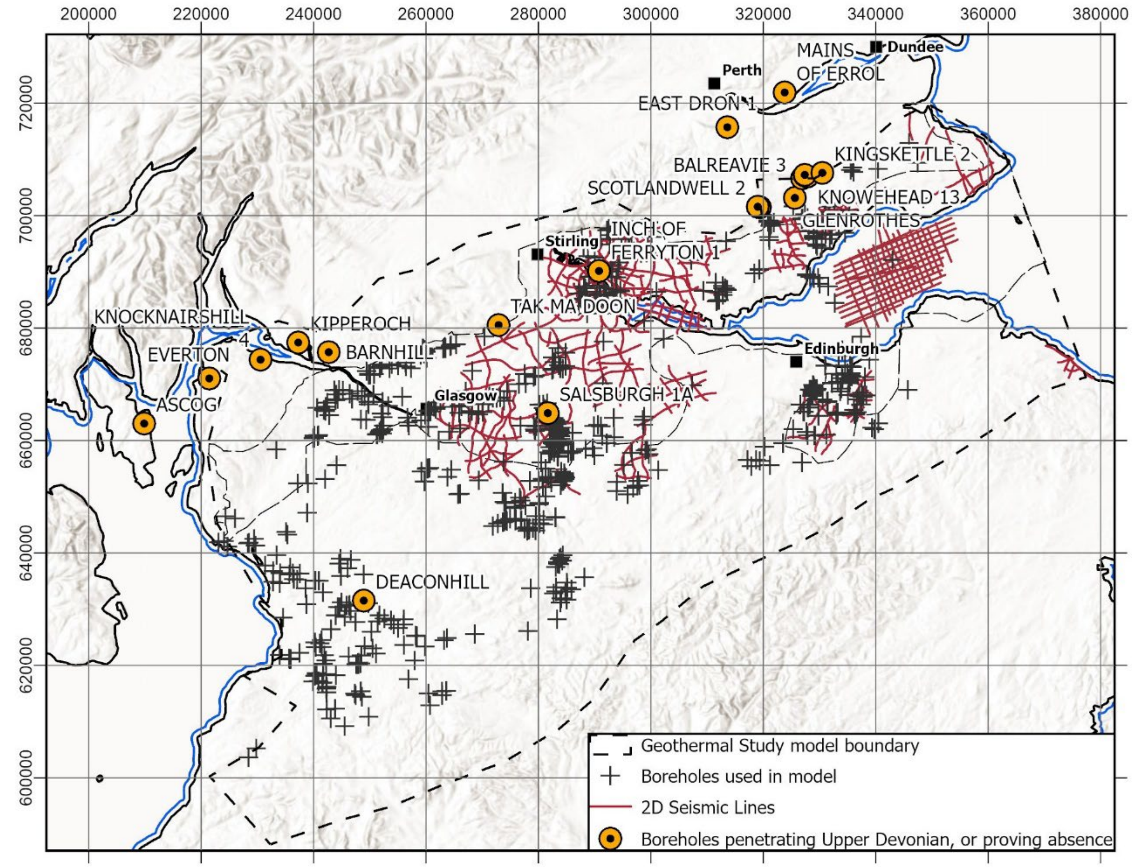

Figure 2 Map of seismic and borehole/well data used in the model, with boreholes proving the top Kinnesswood Formation and base Stratheden Group. Contains OS data © Crown Copyright and database right 2024.

The geological model surfaces were synthesised from previous models created in the Midland Valley, many of which were additionally constrained by mining data, e.g. around and east of Glasgow using the Glasgow Ell Coal spot heights and contours (McCormac 2013) (Table 1).

Table 1 Data sources for the modelled stratigraphical surfaces

Modelled stratigraphic surface name	Borehole picks	Seismic interpretation	Other data (e.g. coal mining data; 100's additional borehole picks)
GT_Base_Permian bPUND	Monaghan (2013)	Monaghan (2013)	Monaghan (2013)
GT_Base_Scottish_Coal_Measures bCMSC	Monaghan (2013)	Monaghan (2013) Monaghan (2012)	Monaghan (2013) McCormac 2013
GT_Base Passage Formation bPGP	BGS Borehole Geology database	Monaghan (2014)	Monaghan (2013)
GT_Base Lower Limestone Formation bLLGS	BGS Borehole Geology database Monaghan (2013)	Monaghan (2013)	Monaghan (2013)
GT_Top Clyde Plateau Volcanic Formation_bGUL	BGS Borehole Geology database	Monaghan (2014c)	Monaghan (2014c)
GT_Top Ballagan bVOLC	BGS Borehole Geology database		Monaghan (2014c)
GT_Base Ballagan bBGN	Re- interpreted for this project	Monaghan (2012)	Outlines Derived from BGS Geology 50k
GT_Base Kinnesswood bKNW	Re- interpreted for this project	Monaghan (2012)	Outlines Derived from BGS Geology 50k
GT_Top Lower Devonian	Re- interpreted for this project		Outlines Derived Browne et al (1987) contour values for Stratheden Group

3.2 MODELLING METHOD

The model was created in SKUA-GOCAD™ using the Structure & Stratigraphy workflow. Due to the complexity of the geology and the variable spatial distribution of the control points, an implicit geological modelling method (e.g. Cowan et al., 2003) was used where all geological units were modelled simultaneously using all the available data held and interpolated within a 3D framework. Rules were applied to ensure that stratigraphic relationships such as onlap and truncation at unconformities were honoured (Figure 3). Due to the complex structural history of the Midland Valley (see Section 1.1 and Figure 1) most of the boundaries between the modelled units were defined as unconformities. However, below the Top Ballagan Formation, there are so few observations that the package to the bottom of the Stratheden Group was modelled with conformable boundaries, otherwise the model would not calculate. The result of this process was a 3D stratigraphical (irregular) grid discretised into 'regions' which correspond to broad stratigraphical units (formations or groups) and bound by unconformities and faults (Figure 1, Figure 3). No attempt was made to model lithological heterogeneities in any of the units in the 3D modelling process.

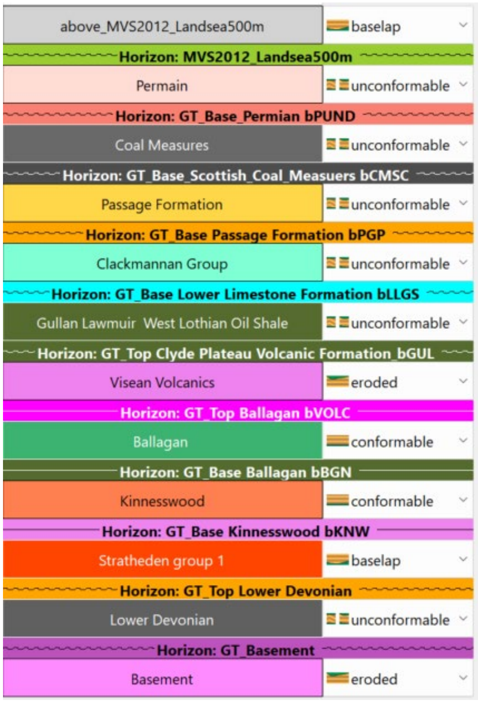

Figure 3 The modelled horizons and stratigraphic relationships incorporated within the 3D geological model.

The implicit model was constructed using a continuous 3D scalar field with a variable cell-size with an area equal to 1500 m^2. The scalar field was varied so that there were 10 cells representing the true stratigraphic thickness of the units. The vertical cells are orthogonal to the base of the bed rather the current vertical. This implicit geological model was used to provide properties to a regular voxel grid with a regular grid size of 500 m x 500 m x 50 m to provide inputs for the Heat-in-Place (HIP) calculator (Section 5). Figure 4 shows the difference between the 3D scalar field model and the voxel model. Although they use different grid sizes, they have comparable levels of detail.

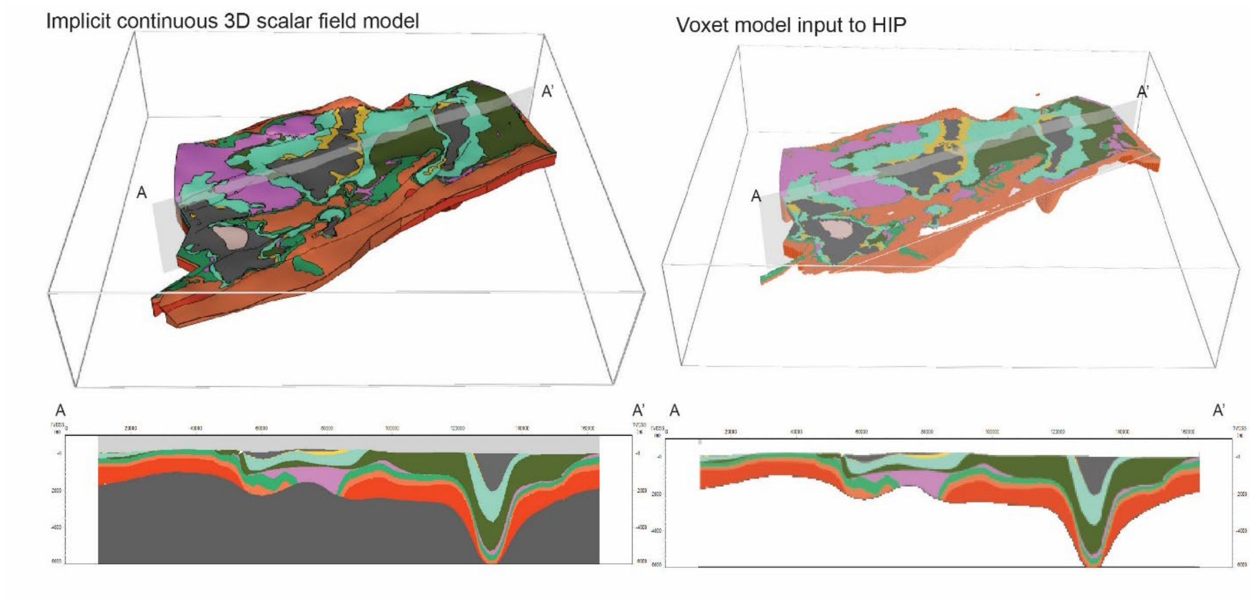

Figure 4 Comparison between the implicit scalar model and the voxel model input into the Heat-In-Place calculator.

3.3 RESULTS

The results from the implicit model (Table 2, Figure 5) show that the top Upper Devonian (Base Ballagan / Top Upper Devonian) has an average depth of -787 m OD (meters relative to Ordnance Datum). It has been modelled as deep as -5800 mOD (Table 2). The modelled thickness of the combined Kinnesswood Formation and Stratheden Group is on average 665 m thick but is modelled as much as 2000 m in some parts of the basin. However, the subcrop extent and southern boundary of the Stratheden Group is derived from the contour maps created by Browne et al. (1987) and has very high uncertainty.

Table 2 Depth ranges of the modelled surfaces in metres relative to Ordnance Datum (mOD).

Depth range (mOD)	Base Permian	Base Coal Measures	Base Passage Formation	Base Lower Limestone Formation	Top Clyde Plateau Volcanic Formation	Top Ballagan	Base Ballagan/ Top Upper Devonian	Base Kinnesswood	Top Lower Devonian / Base Upper Devonian
Minimum	-134	-2087	-1910	-3730	-5257	-5502	-5799	-5998	-6000
Average	47	-39	-112	-383	-665	-618	-787	-881	-1567
Maximum	166	359	369	445	439	435	522	557	183

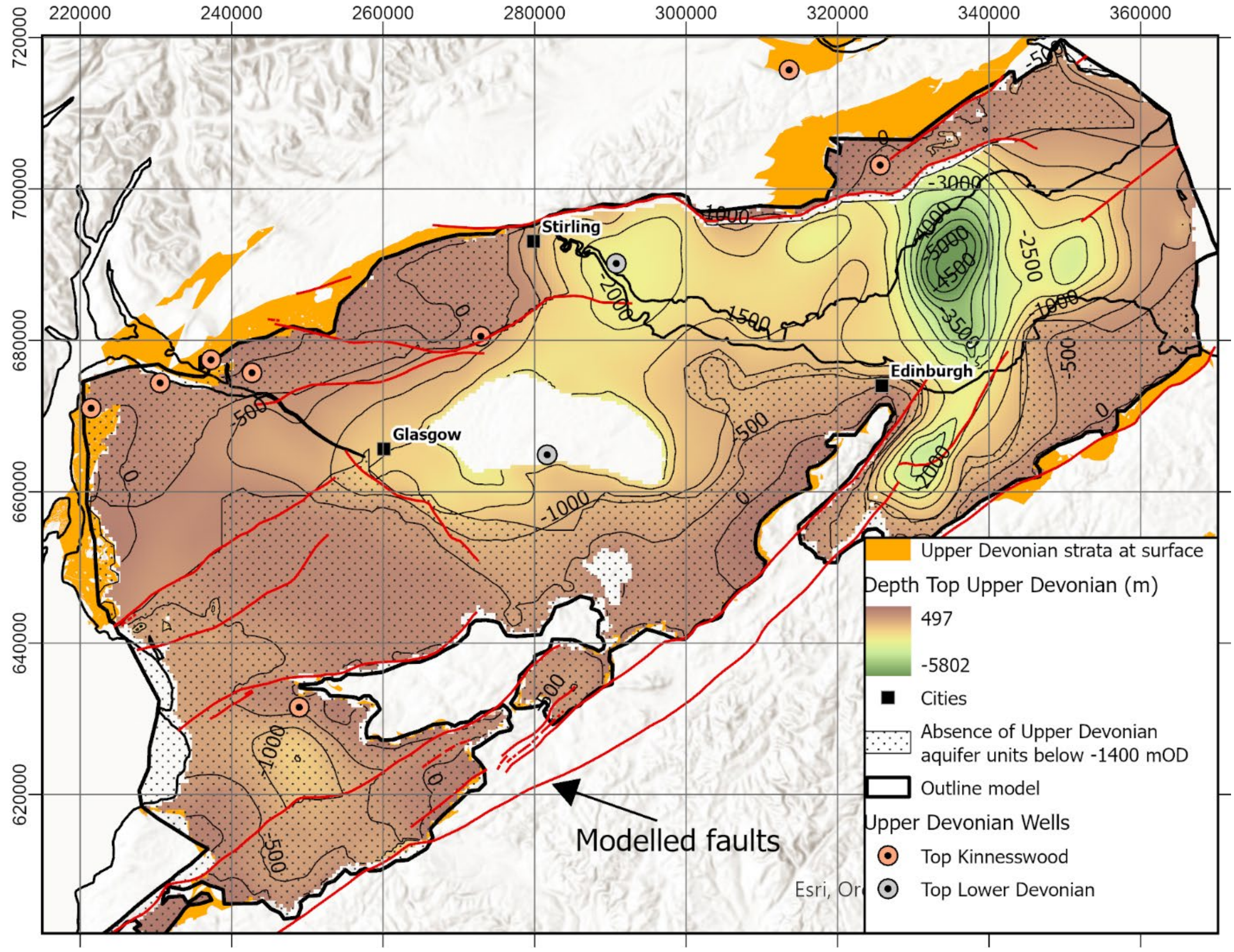

Figure 5 Depth to top of Upper Devonian aquifer (top Kinnesswood Formation) from the regional geological model, relative to Ordnance Datum. Contains OS data © Crown Copyright and database right 2024

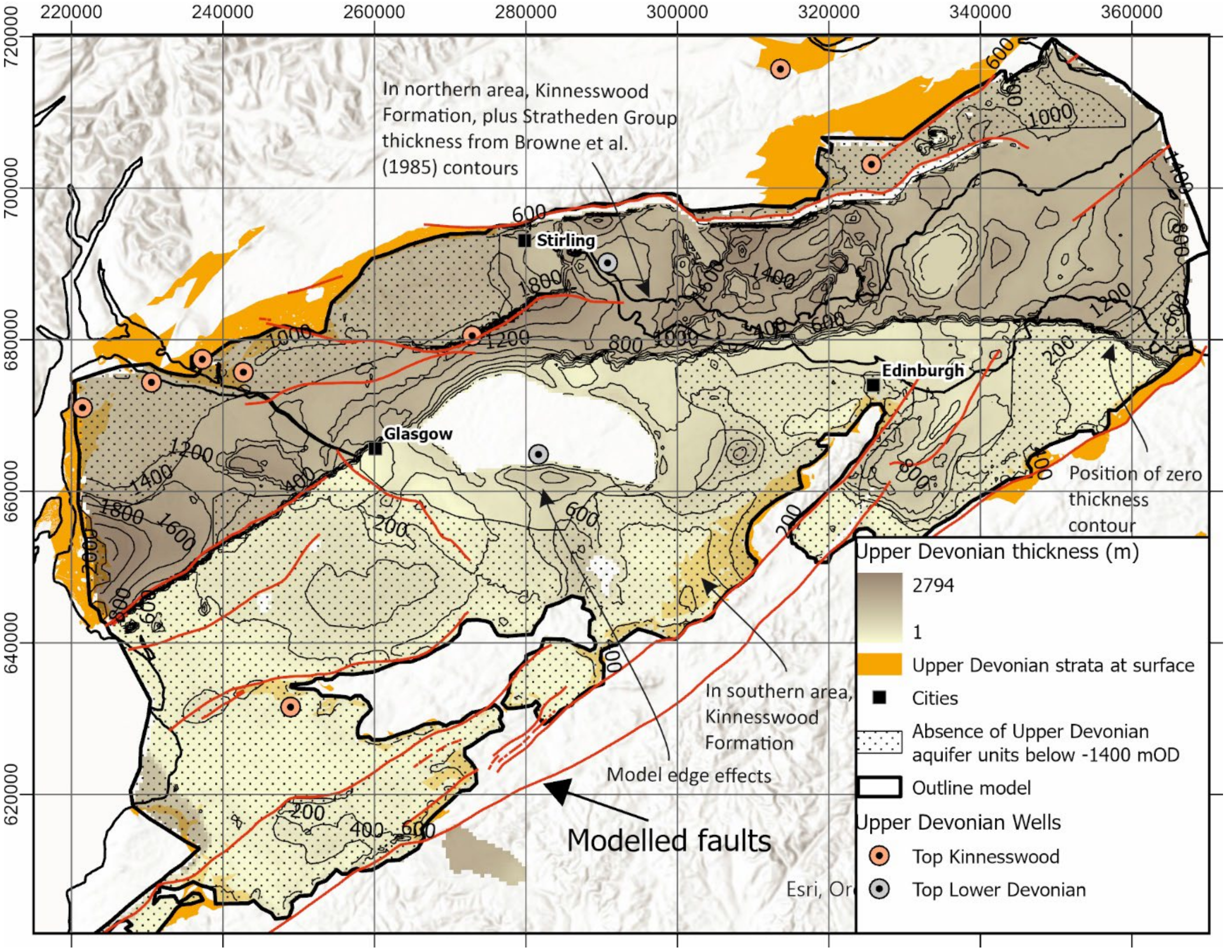

Figure 6 Thickness map of the modelled Upper Devonian units (Kinnesswood Formation and Stratheden Group). Contains OS data © Crown Copyright and database right 2024

The top of the Upper Devonian modelled surface is deepest under the Firth of Forth in the Midlothian-Leven syncline (Figure 5). The Upper Devonian units are not interpreted to be present in Salsburgh-1A borehole corresponding to an area of non-deposition in the Salsburgh-Airdrie-Bathgate area (Figure 5, see Appendix 1 for more detail). The abrupt change in the Upper Devonian thickness map (Figure 6) corresponds to the Stratheden Group deposition and interpreted thickness contours of Browne et al. (1985) in the northern part of the Midland Valley, and interpreted absence of that unit over much of the southern part.

3.4 CAVEATS AND UNCERTAINTY TO THE GEOLOGICAL MODEL

The model is constrained by the data available at the time of construction; other interpretations may be valid. The extent of the geological units is as shown on the published BGS geology maps, taking into account the re-interpretation of the Kinnesswood Formation as Devonian in age. Where data was used from older models (Table 2), it was assumed to be correct unless the model process highlighted an error.

Excepting the Inch of Ferryton well and the challenges of its interpretation and modelling (below and Appendix 1), there are no boreholes/wells that penetrate through the top and bottom of the Upper Devonian in the centre of the basin where it is thickest and deepest (Figure 5, Figure 6). Also in these areas, the Upper Devonian cannot be interpreted on seismic reflection lines due to poor data quality at depth, including effects of Visean volcanic rocks (Figure 1) below which reflectivity is lost.

The model was not forced to fit stratigraphical well markers because this ‘over fitted’ the model to the shallower data and at the target depths (i.e. caused local highs/lows not representative of the wider model). However, it is possible to use the difference between the observed and modelled positions of the strata as an approximation of error (Table 3). This shows that the top of the Kinnesswood Formation (Base Ballagan Formation) has an error approximating 97 m.

Table 3 Difference between observed and modelled positions of well markers in metres

Error	Base Permian	Base Coal Measures	Base Passage Formation	Base Lower Limestone Formation	Top Clyde Plateau Volcanic Formation	Top Ballagan	Base Ballagan	Base Kinnesswood	Top Lower Devonian
Minimum	354	633	276	237	556	556	67	71	596
Average	75	39	27	7	113	148	97	129	833
Maximum	10	120	173	305	80	1	306	521	1070

The variation in the error is also driven by these known limitations:

- Due to the resolution of the model and since only the largest fault structures are included, the depth/thickness of the target interval does not fit with the Inch of Ferryton well and seismic interpretation lying across a fault on a local footwall high which is not part of the model.
- The 500 m resolution of the modelled grids to accommodate the deep basin interpretation, regional model extent and lack of data results in a less detailed and slightly different depth surface than in previous models (e.g. Monaghan et al. 2012; Monaghan 2013; 2014a). For the Passage Formation in particular, it would be possible and beneficial to build a higher resolution model.
- The subcrop of the Stratheden Group is only driven by the work of Browne et al. (1985). It is possible that the Stratheden Group is found further south in the subsurface that has been modelled and this would increase the potential area of geothermal opportunity.

4 Input data for geothermal modelling

4.1 POROSITY ATTRIBUTION

Porosity data reported in the literature has been compiled to perform a statistical analysis on the porosity distribution in the Upper Devonian units. These include data reported in Browne et al. (1985), Brereton et al. (1988), BGS and Heriot-Watt University (2014); Monaghan (2014a), O Dochartaigh et al. (2015), Robinson et al. (2016), Comerford et al. (2018) and Watson (2022).

Porosity values have been reported using various approaches depending on the source of data, including X-CT analysis on core and outcrop samples (Browne et al., 1987; Watson, 2022), 2D thin section porosity (Monaghan et al., 2012; Williams, 2022), helium porosity (Milodowski and Rushton, 2009), sum of fluid porosity, or methods based on the analysis of Density-neutron (DN) and Gamma-Ray (GR) Logs (Shepherd, 2014). The proportion of data reported for each measurement method is summarised in Table 4.

Table 4 Proportion of porosity data per measurement and calculation methods

Method	Number of data	Proportion
2D Thin section porosity	49	18.28%
Helium porosity	17	6.34%
Sum of fluids	1	0.37%
Porosity ΦH (MJ Bird)	50	18.66%
Porosity ΦV (MJ Bird)	50	18.66%
Sub-sample porosity	7	2.61%
Core porosity	7	2.61%
Mean Porosity	75	27.99%
Min Porosity	6	2.24%
Max Porosity	6	2.24%
TOTAL	268	100.00%

Different methods may lead to different estimates of the porosity. For example, lower porosity values were determined for samples from the Kinnesswood and Kelly Burn Sandstone formations by Watson (2022) using the X-CT analysis method relative to those measured from the same formations in the Everton and Glenburn boreholes by Browne et al. (1985; 1987). The difference was attributed to different levels of carbonate cementation/cornstone nodules (natural variability) or as the result of different measurement procedures (e.g. underestimation of the microporosity due to X-CT scan resolution in Watson (2022)).

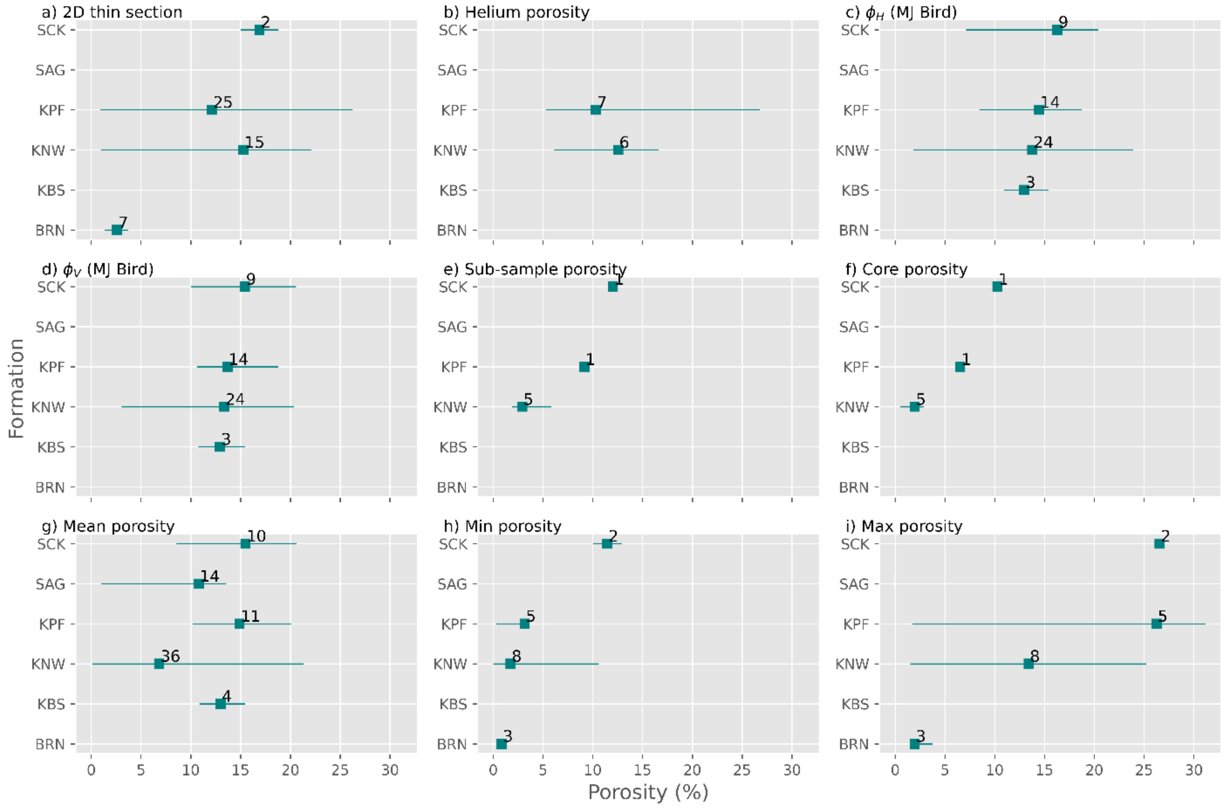

Figure 7 Comparison of the mean and range of porosity values in the different stratigraphical units for different measurements methods. The label corresponds to the number of samples associated to each data point. SCK: Stockiemuir Sandstone; SAG: Stratheden Group undifferentiated; KPF: Knox Pulpit Formation; KNW: Kinnesswood; KBS: Kelly Burn Sandstone and BRN: Burnside formation.

The average, minimum and maximum porosity within each Upper Devonian unit is presented in Figure 8 together with an analysis of the frequency of distribution of porosity values within the succession. Taking all the data together independently from the measurement method, the average and median porosity for the Upper Devonian units is 11.5% ± 6.8% and 12.1%, respectively (Table 5). This is in accordance with the mean porosity of 12% reported for the Kinnesswood Formation based on 50 samples located at < 500 m measured depth from surface in the Glenrothes borehole (Brereton et al. 1988).

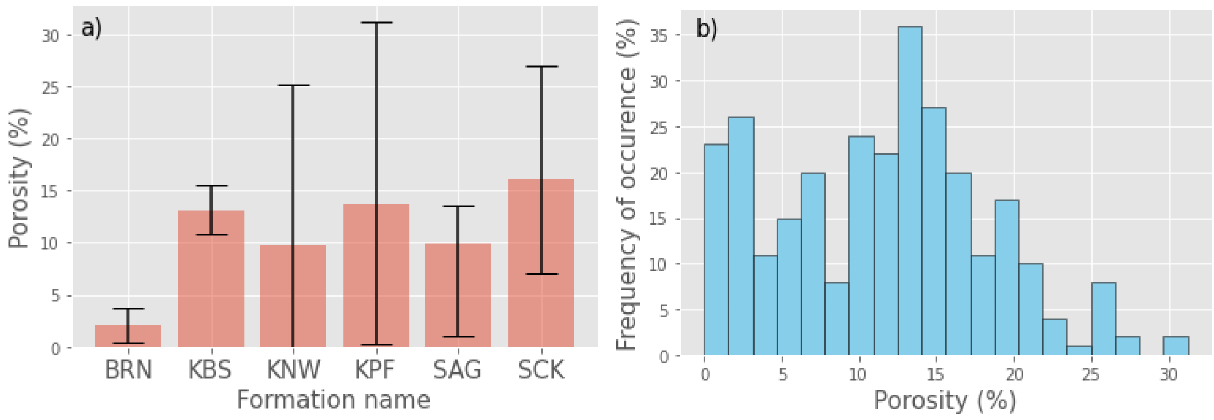

Figure 8 a) Average (red box) and minimum and maximum porosity values (black line) calculated for each formation, all methods taken together. b) Porosity distribution for the Upper Devonian formations (including BRN: Burnside, KBS: Kelly Burn Sandstone; KNW: Kinnesswood, KPF: Knox Pulpit, SCK: Stockiemuir Sandstone and SAG: Stratheden Group undifferentiated), independently of the measurement method.

Table 5 Statistical analysis of the porosity data for Kinnesswood Formation and Stratheden Group (including component formations: BRN: Burnside formation; KBS: Kelly Burn Sandstone; KNW: Kinnesswood; KPF: Knox Pulpit Formation; SCK: Stockiemuir Sandstone; SAG: Stratheden Group undifferentiated). The average values have been calculated for the full data set independently of the method and geological formation.

Formation	Average	Median	std	min	max
BRN	2.1	1.8	1.1	0.5	3.7
KBS	13.1	13.0	1.9	10.8	15.4
KNW	9.8	8.6	6.8	0	25.2
KPF	13.7	13.0	6.7	0.3	31.2
SCK	16.1	15.6	4.5	7.1	27
SAG	9.9	10.8	3.3	1.0	13.6
AVERAGE	**11.5**	**12.1**	**6.8**	**0**	**31.2**

The Upper Devonian units are highly heterogeneous in the proportion of sandstone/mudstone intervals at the bed-scale and between stratigraphical units. Porosity is often measured on samples from outcrops or cores taken from the productive layers of the aquifers, creating a bias towards higher porosity values. This bias is likely to lead to overestimations of the overall productivity of the Upper Devonian aquifers and, in the geothermal modelling (Sections 5 and 6), of the total Heat-In-Place. A few samples from the cemented and muddy intervals of the Upper Devonian target intervals suggests that porosities as low as 0.09% can be found in the Kinnesswood Formation (KNW), with minimum of 1.33% measured on samples from the Burnside Sandstone Formation (BRN) and 3.17% for the Knox Pulpit Formation (KPF).

In Milodowski and Rushton (2009), this large range of porosity values resulting from the diverse lithologies and cementation levels has been observed from the analysis of thin sections (2D porosity):

- Example of porous sample [BEB7503]: Kinnesswood Formation sandstone in Balreavie No.3 Water (at 22.50 m depth), described as ''Medium to coarse lithic-feldspathic sandstone with common mudstone clasts up to 5mm''. The total porosity varies between 19.4% – 22.1%.
- Example of low porosity sample [SBO9278]: Burnside Sandstone in Mawcarse Station Water borehole (at 22.63 m depth), described as ''Fine to coarse sandstone with pervasive carbonate and patchy kaolinite''. The total porosity ranges between 1.3% – 3.7%.

- In the Glenrothes borehole, the porosity estimates for the Kinnesswood Formation varies between 6.7% (428 m deep sample described as a coarse breccia/dolocrete, dolomite cemented) to 21.3% (388 m deep sample described as a close-packed medium grained sandstone with patchy dolomite cement and common oversized pores).

The porosity of the Upper Devonian units has been suggested to reduce with increasing depth (Brereton et al. 1988). Given the number of stratigraphic units with variable thickness and lithology, a range of methods was tested to best represent the porosity values that account for those heterogeneities to feed into the geothermal model. This included the determination of 1) a Net-To-Gross porosity (i.e. based on the relative proportion of high porosity and low-porosity intervals in the KNW and KPF formation) and b) a harmonic mean porosity calculated based on the rock type percentage and formation thicknesses from boreholes located in the MVS. However, none of these methods provided robust results given the bias and scatter of the limited data points.

A simpler method was therefore applied, consisting of calculating the average porosity for all of the Upper Devonian units, based on the average of all the available porosity values for the KNW, KPF, the combined BRN, KBS, SCK and the SAG data samples (independently of the porosity measurement method), and weighted on the formation thicknesses. Here, the average formation thickness at the scale of the MVS basin was considered, leading to a harmonic mean/median porosity Φ = 11.4% with a standard deviation of 6.8% (Table 6).

Table 6 Simplified approach to calculate the average porosity of the Upper Devonian units, based on the average of all porosity values available in each formation and the average formation thicknesses. KNW: Kinnesswood Formation, KPF: Knox Pulpit Formation and SAG: Stratheden undifferentiated.

	Porosity	Thickness (m)	Relative thickness (%)
KNW	9.8%	400	36.0%
KPF	13.7%	150	13.5%
SAG (other)	12%	560	50.5%
Weighted average porosity		11.4%+/- 6.8 %	

4.2 COMPUTING AN AVERAGE GEOTHERMAL GRADIENT

The average geothermal gradient for the Upper Devonian units is calculated using a compilation of data from diverse sources. The sources of temperature data from 79 boreholes include temperature logs from deep hydrocarbon and coal-bed methane wells not included in previous analyses, long-term test reports, UK Geothermal Catalogue (Burley et al. 1984; Rollin 1987), BGS reports (Browne et al., 1985), the UK Geoenergy Observatories borehole (Monaghan et al. 2017), the Glenrothes geological well completion report and hard copy logs of borehole temperatures.

Temperature data are classified according to the measurement types in the UK Geothermal Catalogue. Equilibrium temperatures include EQM (Equilibrium measurement), VST (Virgin Strata temperature) and DST (Drill-stem test measurement). For more recently drilled deep boreholes where no equilibrium measurements were recorded and no corrected temperatures are available from the literature (e.g. Airth-6, Bandeath 1, Firth of Forth 1, Inch of Ferryton 1, Longannet 1, Meadowhill 1), corrections have been applied on the borehole temperature (BHT) and log (LOG) temperatures according to equation 1:

$$T_{corr} = T_{measured} \times \left(1 + \frac{1}{dt} + \frac{1}{dt^2}\right) \quad (1)$$

With T_{corr} representing the corrected temperature, $T_{measured}$ the uncorrected (measured) temperature and *dt* the time since circulation in hours. This was estimated based on a comparison of the geophysical data acquisition time relative to the drilling completion date (e.g. 6h, 24h, 36h, 72h) and follows the method outlined in Rollin (1987).

Corrections were also applied to measurements in the Bargeddie 1, Clachie Bridge, Craighead 1, Hallside, Linkfield, Milton of Balgonie No. 2, Milton of Balgonie No.3, Pumpherston, Salsburgh 1A, Salsburgh 2 boreholes based on the available time since circulation from the geothermal catalogue.

The linear regression applied on the corrected temperature-depth data suggests a geothermal gradient of 26.6°C/km for the full dataset and 26.4°C/km for temperatures measures at depths > 500 m. This gradient decreases to 24.3°C/km for depths < 600 m (Figure 9). This is higher than the range of values reported in Browne et al. (1987), where the geothermal gradient for the Carboniferous and Devonian basins was shown to vary between 20ºC/km and 25ºC/km depending on the relative proportion of rock types. A uniform temperature gradient of 22.5ºC/km was considered representative for the MVS based on the most accurate measurements from 4 virgin strata temperature and drill stem tests. Conversely, the geothermal gradient calculated here is lower than the values reported in Gillespie et al. (2013) who calculated a gradient of 30.5ºC/km in the top 1.5 km, 35.8ºC/km between 1.5 km and 3.5 km and 46.7ºC/km between 3.5 km and 5 km using a combination of onshore and offshore borehole data.

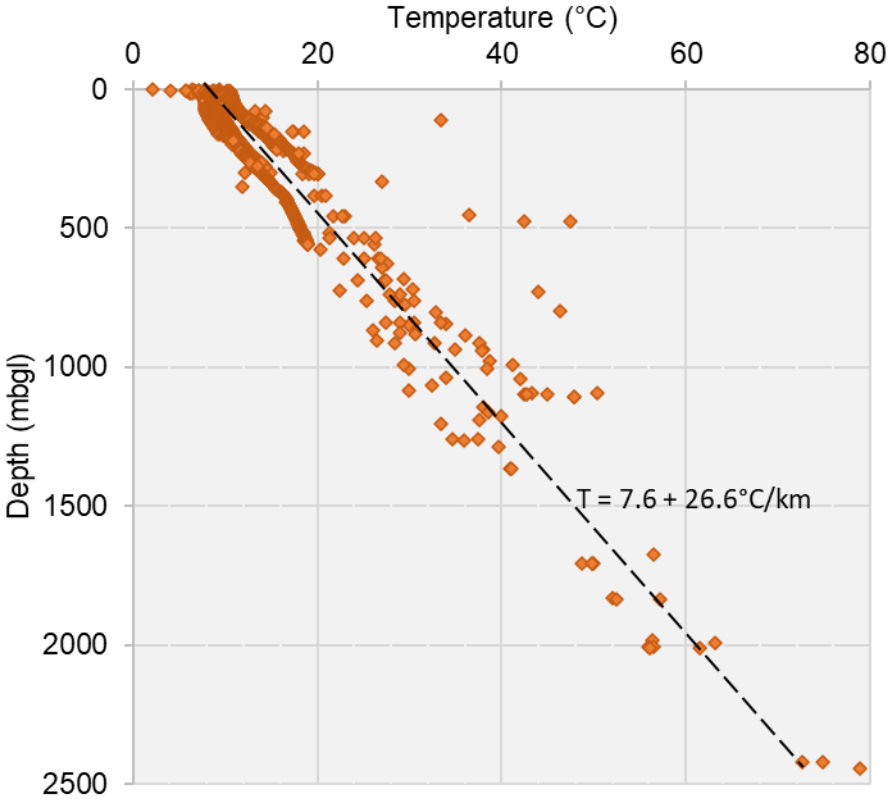

Figure 9 Temperature-depth distribution for the Upper Devonian dataset used for the onshore Midland Valley of Scotland. The dashed line represents the mean geothermal gradient of 26.6ºC determined via linear regression.

4.3 CAVEATS AND LIMITATIONS TO THE GEOTHERMAL MODEL INPUT DATA

- Surface outcrop and shallow boreholes (less than 200 m deep) provide much of the information for the aquifer units of interest. Several authors have noted that boreholes and core samples from these depths are not likely to be representative of subsurface conditions at geothermal target depths greater than 1km (Browne et al. 1985; Milodowski and Wilmot 1985; Watson 2022, Westaway and Younger 2013)
- Porosity is a key input to the Heat-In-Place model, yet there are limited values from the target intervals, particularly from rock samples recovered from depth and from units of the Stratheden Group, excepting the Knox Pulpit Formation. On plotting the dataset with depth, the spread of the porosity values is large, and a regression line cannot be fitted.
- There is systematic bias in sampling towards shallower rock samples and towards known aquifer units, the effect of which is that porosity values are believed to be skewed to high values.

- The characteristics of the target aquifers, where assessed for groundwater at shallow depths, is believed to be dominated by fissure/fracture flow; the flow characteristics at depth will be dependent on the extent and number of open (transmissive) fractures (Downing and Gray 1986). Fissure/fracture flow is not included in the porosity value included in the Heat-In-Place calculation; however, this may counteract the systematic bias noted above for core porosity analyses.
- The temperature gradients measured from more recent deep boreholes than the 1980's studies were corrected for the time since circulation, when available. The effect of mining and corrections for the effect of paleoclimate on shallow temperature measurements were applied on data reported in Watson et al. (2019, 2020) and Watson (2022). Their analysis showed that temperatures uncorrected for paleoclimate tend to underestimate the geothermal gradient and the geothermal heat flux by c. 20 W/m^2 in some areas. A paleoclimate correction has not been evaluated in this study. The average geothermal gradient calculated in this study may be underestimated, leading to a bias in calculated Heat-In-Place towards the lower end.

5 Geothermal modelling method

Similarly to the approach used by Jones et al. (2023) for the estimation of the geothermal potential of the early Carboniferous Limestones in Central and Southern Britain, the Heat-in-Place (HIP) and recoverable heat (H_{rec}) for the Upper Devonian units are calculated using the 3DHIP simulator (Piris et al. 2021). 3DHIP-Calculator is a free software written in MATLAB™ and publicly distributed by the Institut Cartogràfic and Geològic de Catalunya (ICGC). The software uses stochastic methods to estimate the deep geothermal potential of hot sedimentary aquifers (HSA) using the USGS volumetric HIP method (Garg and Combs 2015; Muffler and Cataldi 1978). Monte Carlo simulations (Shah et al. 2018) are used to solve for the HIP and H_{rec} for a range of uncertain variables/input parameters, based on the 3D geological and thermal models provided by the user. Results are presented in the form of probability density functions that can be used to derive the geothermal resource representing different probabilities. P10, P50 and P90 correspond to the 10th, 50th and 90th percentiles of the calculated cumulative distribution function and are referred to as "proved", "probable" and "possible" resources.

5.1 HEAT-IN-PLACE

The volumetric HIP method calculates the heat energy (in joules) stored in the both the rock mass and the formation fluid and is a common method for estimating resource potential in deep geothermal reservoirs. The HIP is given by Eq. 2:

$$HIP = V\left[\Phi\rho_f c_f + (1-\Phi)\rho_r c_r\right](T_r - T_0) \qquad (2)$$

Where V is the cell or voxel volume (m^3), Φ is the porosity (%), ρ_f and ρ_r are the fluid and rock densities (kg/m^3) respectively, c_f and c_r are the fluid and rock specific heat capacities (kJ/kg°C) respectively, T_r is the voxel (reservoir) temperature and T_0 is the reference temperature (e.g. reinjection, abandonment, ambient temperature).

Here, a reinjection temperature of 25°C is used to calculate the HIP in the Upper Devonian units, in accordance with the value used in the literature for deep sedimentary aquifers (e.g. Rollin et al., 1995).

Depending on the depth of the resource considered, different approaches have been used in the past to constrain the volume of hot sedimentary aquifer resources in the UK, including the choice of a reference temperature. Examples of approaches are summarised here, as some comparisons are made below with the Midland Valley results obtained in this report. Among previous UK work, Rollin et al. (1995) estimated the geothermal resources of Permo-Triassic basins in the UK for all resources greater than 40°C using a simple volume model of HIP within each of the recognised aquifers. The reference temperature T_0 was defined so as to represent the temperature at the ground surface (c. 10°C). In Jackson (2012), the reservoir volume was constrained based on cut-off temperatures greater than 45°C, 65°C, 40°C and 65°C for the East England, Wessex, Worcester and Cheshire Basins respectively. The HIP was calculated using a single average temperature for each reservoir and a reference temperature of 25°C (Busby, 2014). Alternatively, Pasquali et al. (2010) defined the reservoir volume using the radius of influence of a geothermal doublet over a period of 25 years. For example, the Early Carboniferous Limestone resource potential was determined assuming an area of 22.5 km^2 and based on the heat theoretically available using two well doublets with a base temperature of 40°C. Finally, Jones et al. (2023) assessed the HIP for the Central and Southern Britain Early Carboniferous Limestone basins using an upper depth cut-off of 1 km and 1.2 km, respectively, corresponding to a reservoir temperature of 50°C, in accordance with the method employed in this analysis.

5.2 RECOVERABLE HEAT

The recoverable heat (Eq. 3) is calculated using the 3DHIP-Calculator based on the method described in Piris et al. (2021.) The recoverable heat provides an estimate of the producible thermal power (in kilowatts), based on assumptions regarding the conversion efficiency of the heat exchanger c_e (%), a recovery factor R (%), the expected lifetime of a geothermal project T_{live} (sec), and the proportion of time a plant is likely to be operating (plant factor) P_f (%).

$$H_{rec} = HIP \frac{c_e R}{T_{live} P_f} \quad (3)$$

Different approaches and parameters have been used in the past to determine the share of Heat-In-Place technically available for recovery. In Rollin et al. (1995), the proportion of the geothermal resource that is available for development is referred to as the *identified resource* and is defined as a function of the hydraulic properties of the aquifer, the method of abstraction or recovery factor (F) and the reject temperature of the disposal fluid (T_j) (Eq. 4):

$$H_{rec} = HIP\ F \frac{T_r - T_j}{T_r - T_0} \quad (4)$$

Where T_r and T_0 correspond to the reservoir and ground surface temperature, respectively. Whilst the UK identified resources had previously been calculated using T_j and F varying from 10°C to 30°C and 0.10 to 0.25, respectively, Rollin et al. (1995) used a reject temperature of T_j = 25°C (as in Downing and Gray, 1986) and a recovery factor of 0.33. Geothermal resources were calculated for reservoir temperatures greater than 40°C. One of the key differences with the 3DHIP method is the consideration of the net-to-gross volume (i.e. the proportion of aquifer with sufficient porosity and permeability to provide a reservoir).

Alternatively, Pasquali et al. (2010) assessed the total heat power stored in geothermal reservoirs in Northen Ireland using the volumetric approach of Muffler and Cataldi (1978) and calculated the recoverable heat assuming a reject temperature of 40°C, a load factor of 0.75 and lifetime of 25 years (Eq. 3). In Jones et al. (2023), a recovery factor of 0.1 and reinjection temperature of 21°C was used to determine the recoverable heat of the Early Carboniferous Limestones, using the 3DHIP-Calculator (Piris et al. 2021).

The volumetric method and 3DHIP tool can provide an estimate of the theoretical recoverable heat at regional scale. In comparison, the Doubletcalc tool (Mijnlieff et al. 2014) calculates the temperature and pressure development around aquifer doublet systems within a specified region of interest.

5.3 INPUT DATA

Reservoir petrophysical properties (e.g. porosity, fluid density and specific heat capacity, rock density and specific heat capacity) and model parameters (i.e. recovery factor, reinjection temperature, conversion efficiency, plant factor and mean plant lifetime) are input as probability distribution functions (PDFs) and are listed in Table 7. Based on the analysis of the data compiled within the scope of this report, a porosity of 11.4% +/- 6.8% is attributed to the Upper Devonian formations. The density and heat capacity were attributed based on data reported in Watson (2022). Those were calculated as the average of the harmonic mean densities from boreholes located in the MVS (i.e. product of the percentage of rock type in each formation determined from BGS borehole logs and the density/heat capacity of each lithology reported in the literature). The range of density values for each formation agrees with the values for the Devonian reported in Downing (1988).

The thermal model is defined using a surface temperature of 8°C and temperature gradient of 26.6°C/km. The surface temperature was calculated as the average of the surface temperatures across the MVS based on data from Met Office (2022). The geothermal gradient is assumed to be constant over the study area and was determined from corrected borehole temperatures (Figure 9; Section 4.2).

The volume for the Upper Devonian units is derived from the 3D geological model for the MVS exported with a spatial resolution of 500 m x 500 m x 50 m (x, y, z). An upper depth cut-off of 1.4 km is applied to constrain the calculation of the Heat-in-Place and recoverable heat resources to temperatures higher than approximately 50°C, which is judged to be the minimum temperature required for direct-use applications of geothermal energy. The resulting Heat-In-Place values are an estimate of the total geothermal energy contained within the reservoir volume below the 1.4 km cut-off depth.

Table 7 Model properties and inputs to the 3DHIP calculator for the Upper Devonian model. The values in brackets represent the standard deviation or range provided as input to the 3DHIP tool.

Property	Upper Devonian	Source
Thermal Gradient [ºC/km]	26.6°C/km	Compiled data (this report)
Surface Temperature [ºC]	8°C	MetOffice (2022)
Porosity [%]	11.4% [+/- 6.8%]	Compiled data (this report)
Rock density [kg/m³]	2495 [+/- 80]	Watson (2022), in accordance Downing (1988), O Dochartaigh et al. (2015)
Rock Specific Heat Capacity [J/kgºC]	0.943 [+/- 0.03]	Watson (2022)
Fluid density [kg/m³]	1040 [+/- 10]	Carboniferous Limestone model / Veldkamp et al., 2021
Fluid Specific Heat Capacity [J/kgºC]	3.8 [+/- 0.1]	Carboniferous Limestone model / Veldkamp et al., 2021
Reinjection Temperature [ºC]	25°C	e.g. Rollin et al. (1995)
Recovery Factor [-]	0.1 [0.05 – 0.2]	Based on Williams (2007)
Plant Factor [-]	0.95	Default value (Piris et al. 2021)
Mean Plant Lifetime [years]	30	Default value (Piris et al. 2021)
Conversion Efficiency [-]	0.85	Default value (Piris et al. 2021)

6 Geothermal modelling results

The probability distribution for the HIP (PJ) and H_{rec} (MW) in the Upper Devonian units are calculated using the 3DHIP calculator (Piris et al., 2021) over 2000 simulations (Table 8). Although 10,000 trials are industry standard, the number of simulation steps is reduced to decrease the computational time whilst ensuring similar results to those obtained with a higher number of steps. The predicted temperature and calculated HIP (PJ/km^2) and H_{rec} (MW/km^2) distribution for depths greater than 1.4 km (at which the temperatures averages 50ºC) are displayed in Figure 10 and Figure 11, respectively. Results detailed in Table 8 indicate the P10, P50 and P90 HIP (converted to EJ) and H_{rec} (converted to GW) for the Kinnesswood Formation only, for the full Upper Devonian succession within the modelled MVS study area, and for the full Upper Devonian succession located onshore and within 1 km from the coastline offshore.

Table 8 Total Heat-In-Place (EJ) and recoverable heat (GW) for the Kinnesswood Formation only, for the Upper Devonian units (Kinnesswood Formation and Stratheden Group), and the part of the Upper Devonian Units situated onshore and within 1 km from the coastline offshore, for units located between 1.4 km and 5.99 km depth. The recoverable heat is calculated assuming a reference temperature T_0 = 25°C.

	Kinnesswood Formation		Upper Devonian units		Upper Devonian units Onshore +1 km	
	HIP (EJ)	**H_{rec} (GW)**	**HIP (EJ)**	**H_{rec} (GW)**	**HIP (EJ)**	**H_{rec} (GW)**
P90	99.0	7.36	312.5	23.21	223.1	16.6
P50	107.2	10.90	341.7	35.56	243.9	25.4
P10	114.0	16.22	361.1	51.43	257.8	36.7

Figure 11 suggests that the greatest temperatures and HIP are located offshore within the Firth-of-Forth, distant from the heat demand and for which techno-economics would be significantly different. Using Eq. 5, we find that about 71% of the calculated total HIP and H_{rec} is situated onshore and within a limit of 1 km away from the coastline. This value is the same independently of the percentile used (e.g. P10, P50 or P90).

$$HIP \quad = \frac{\sum HIP}{\sum HIP} \qquad (5)$$

Where HIP represents the vertical sum of the voxels located below the 1.4 km depth cut-off in the Upper Devonian reservoir, $\sum HIP$ the total HIP in the study area, and $\sum HIP_{onshore}$ the sum of the HIP for voxels located onshore and within 1 km from the coastline. The same approach was used to calculate the share of onshore modelled recoverable heat.

Resultant Heat-In-Place values for onshore and within 1km of the coastline are P10 = 257.8 EJ, P50 = 243.9 EJ and P90 = 223.1 EJ, and P10 = 36.7 GW, P50 = 25.4 GW and P90 = 16.6 GW for modelled recoverable heat.

6.1 RESERVOIR (AQUIFER) TEMPERATURE

A statistical analysis of the temperature distribution in the Upper Devonian units is calculated by the 3DHIP calculator for reservoir (aquifer) depths greater than 1.4 km, using a surface temperature of 8°C and geothermal gradient of 26.6°C/km. Histograms of temperature distribution generated by the calculator indicate that most of the reservoir accesses temperatures ranging between 45°C and 95°C. Maximum temperatures of up to c. 170°C are accessed in the deepest part of the basin (Figure 10), in the Midlothian-Leven syncline where the base of the Upper Devonian reservoir reaches depths of ~5 km (Figure 5). According to the classification from Hochstein (1990), the Upper Devonian units in the MVS can be classified as a low-moderate temperature resource.

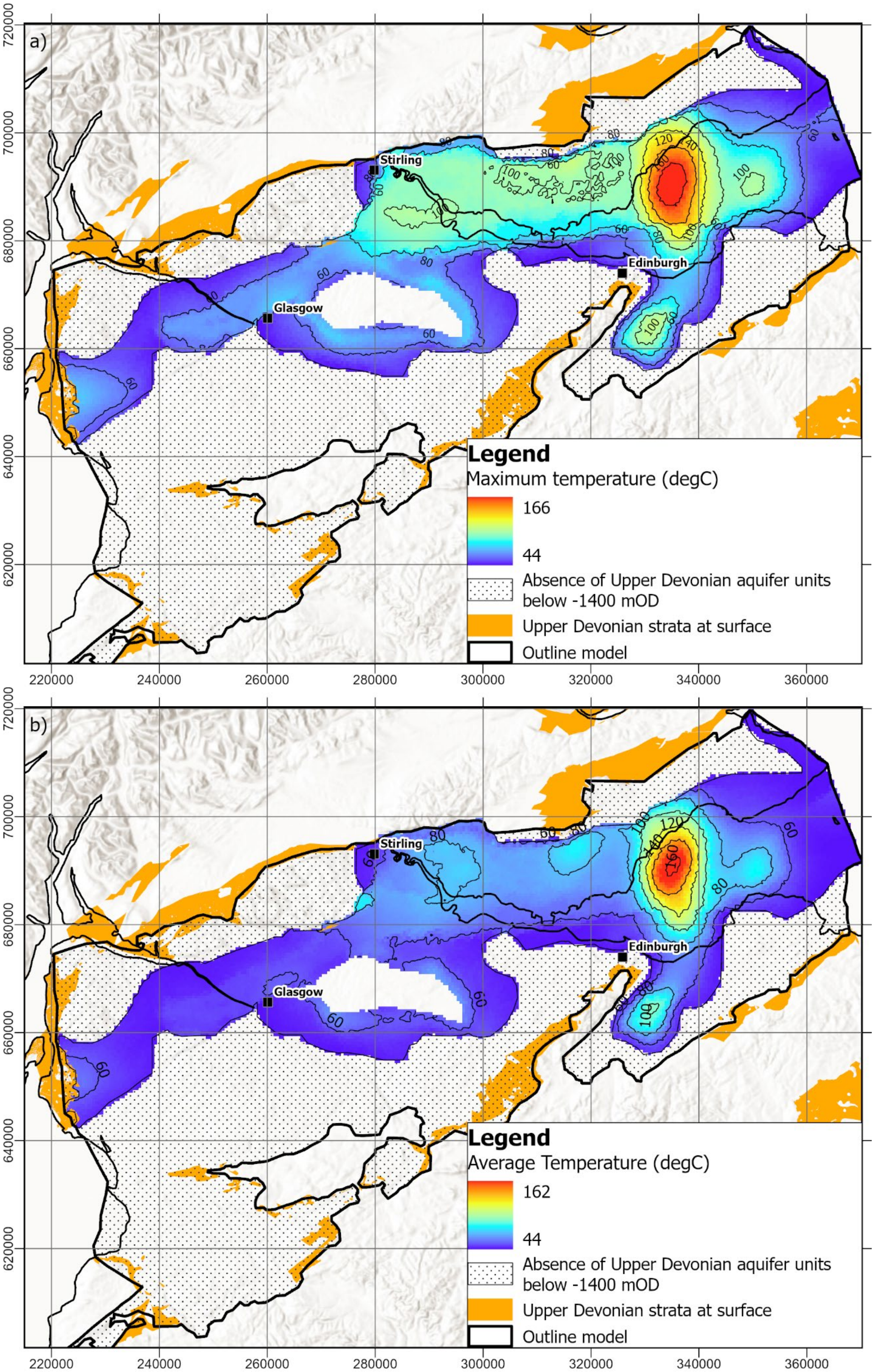

Figure 10 Maximum (top) and average (bottom) reservoir temperature for the Upper Devonian units within the area used for the HIP calculation (depth relative to OD > 1.4 km). Contains OS data © Crown Copyright and database right 2024

6.2 UPPER DEVONIAN TARGET UNITS

Figure 11 shows the P50 HIP and P50 H_{rec} for the Upper Devonian (Kinnesswood Formation and Stratheden Group) units for depths beneath 1.4 km, where the reservoir is expected to deliver temperatures greater than c. 50°C. The highest HIP potential is found in the offshore part of the Midlothian-Leven Syncline. Although the base of the Upper Devonian is found at depths shallower than 3.5 km towards the central and western areas of the MVS, the modelled units thickness reaches a maximum of about 2.2 km south-east of Stirling, which, together with a depth from 900 m (58°C) results in the high HIP values in this area (see Figure 5 and Figure 6).

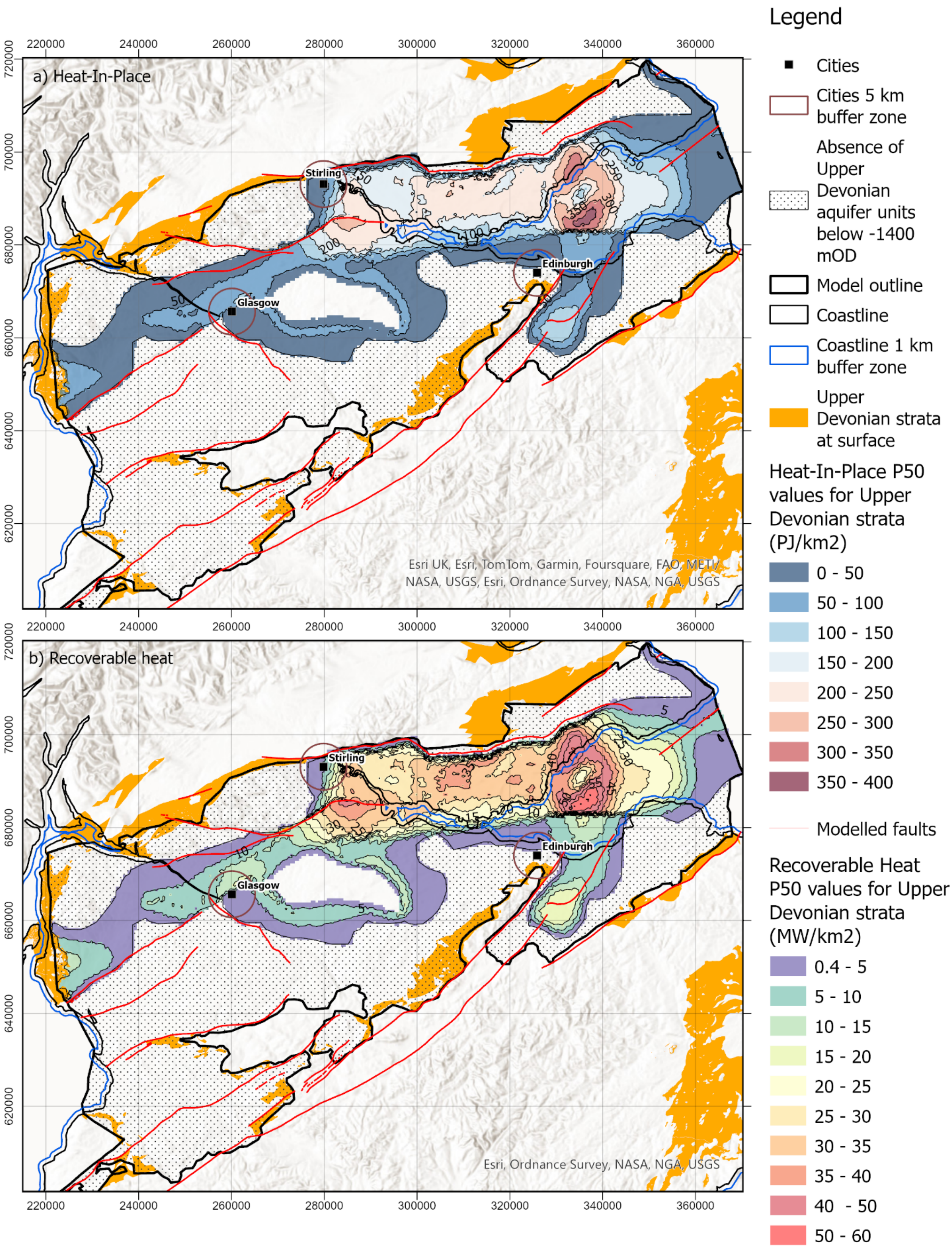

Figure 11. a) Heat-In-Place (HIP, PJ/km^2) and b) recoverable heat (H_{rec}, MW/km^2) for the Upper Devonian units. The HIP and H_{rec} values represent the vertical sum of the voxels HIP and H_{rec} within the considered reservoir depth range divided by the surface area of the grid cells (0.5 x 0.5 km^2), to provide a value per km^2. Contains OS data © Crown Copyright and database right 2024

The average modelled Heat-In-Place and recoverable heat are calculated around the largest urban centres in the MVS using a buffer zone with a radius of 5 km. In the vicinity of Stirling, the modelled HIP averages 69 PJ/km^2 (P50), against 23 PJ/km^2 for Edinburgh and 46 PJ/km^2 for Glasgow (Figure 11a). Although the top Devonian is found at a similar average modelled depth to the northeast of Edinburgh (c. -860 m) to that at Stirling, the modelled thickness of the units is reduced to c. 400 m. In Glasgow, the higher modelled HIP value is mostly controlled by the greater depth of the Upper Devonian units, which extends to about -1.6 km relative to OD, with a mean reservoir temperature of c. 54°C.

The greater thickness of the Upper Devonian units between Stirling and the north of Edinburgh is the essential control on the heat potential in this area. The maximum HIP in the area extending between those main urban centres is c. 200 PJ/km^2. Though the porosity is lower, the larger depth/thickness of the Upper Devonian units result in higher values than the modelled geothermal resource potential for the Mesozoic saline aquifers in the Cheshire Basin, East Yorkshire-Lincolnshire Basin (maximums of 150 PJ/km^2), for the Worcester Basin (maximums of 125 PJ/km^2) and Wessex Basin (maximums of 25 PJ/km^2) (Rollin et al. 1995). The resource estimation for the Upper Devonian of the MVS is however in the range of estimates for the Palaeozoic Early Carboniferous Limestone (Jones et al. 2023), with values averaging 200 PJ/km^2 in Northern England (e.g. Doncaster) and of up to 400 PJ/km^2 to the northwest of Manchester and to the south of Bath in Southern England. The Fell Sandstone was calculated to contain a resource of up to 150 PJ/km^2 north of Darlington, in northeast England (Sutton et al. 2022).

In accordance with the HIP estimates, the highest potential for heat recovery (40 MW/km^2) is modelled as located below the Firth of Forth. The recoverable heat H_{rec} reaches an average and maximum P50 of 7.2 MW/km^2 and 22.6 MW/km^2 below and within a 5 km radius around Stirling, whilst averages of 2.4 MW/km^2 and 4.8 MW/km^2 and maximums of 3.8 MW/km^2 and 12.1 MW/km^2 are modelled below Edinburgh and Glasgow, respectively (Figure 11b). The P10 H_{rec} depicts more optimistic values, with maximums of 32.7, 5.5 and 17.5 MW/km^2 below Stirling, Edinburgh and Glasgow, respectively. The tentative values of heat recoverable ranging from *c.*2-33 MW/km^2 under cities are of similar magnitude to the heat demand shown on Scotland's heat map (Scottish Government, 2024).

The following section discusses the significant uncertainties in these estimations.

6.3 CAVEATS AND LIMITATIONS TO THE GEOTHERMAL MODEL OUTPUTS

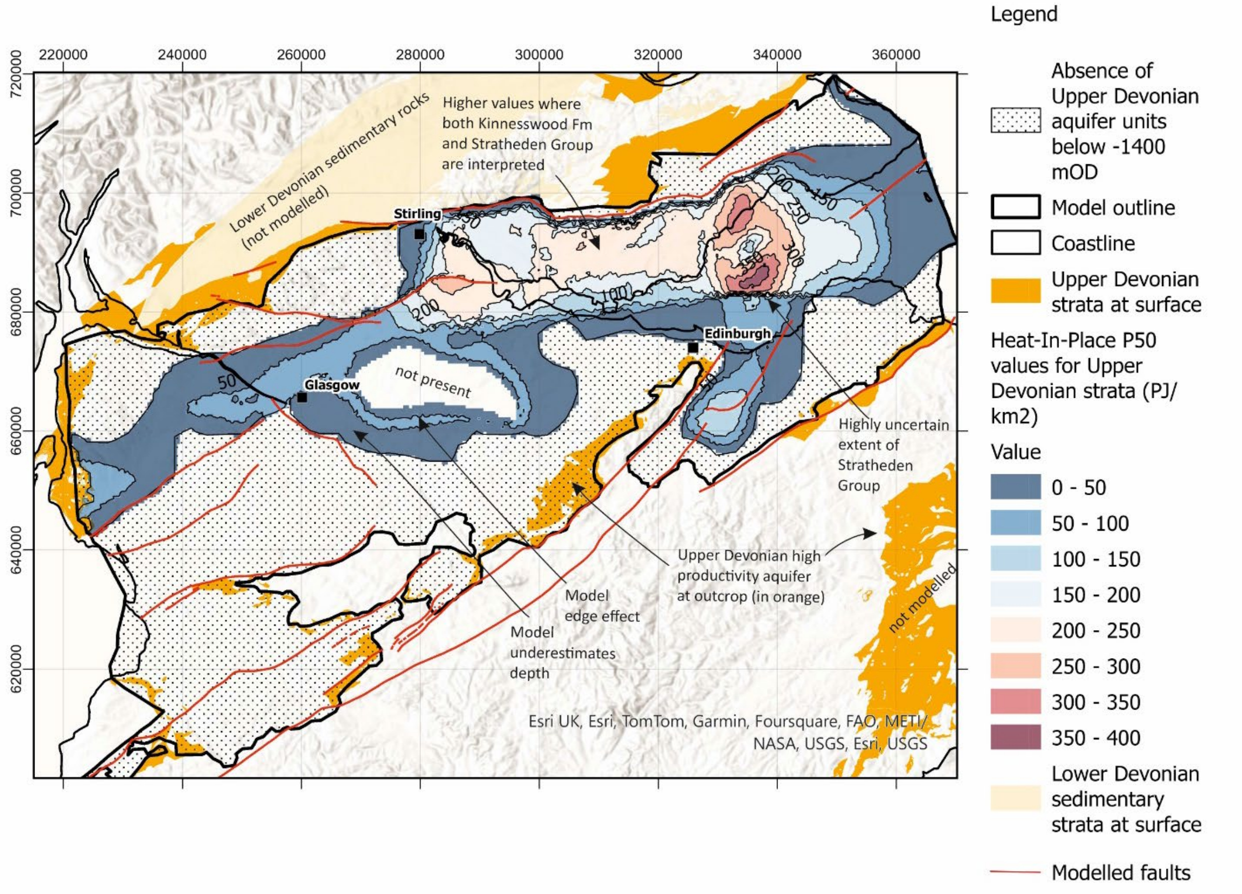

Figure 12 Summary of Upper Devonian hot sedimentary aquifer modelled Heat-In-Place estimation for central Scotland, where deeper than 1.4 km for temperatures over *c.*50 °C, with some limitations annotated. Contains OS data © Crown Copyright and database right 2024

The geothermal model outputs are presented with high uncertainty. This derives from

- the deeply buried extent, depth and thickness of the target units being poorly defined by data, including the challenges of interpretation beneath a series of extremely variable volcanic units and unconformities
- input parameters being summarised (e.g. porosity, temperature gradient) and model resolution being coarse, applicable to regional modelling and data availabitiy

Limitations to the geothermal estimation derived from areas where geological modelling has proved challenging, for example (Figure 12):

- an overthickened edge effect around the area where the target units are interpreted as absent in the centre of the model;
- an overthickened model in the south of Midlothian syncline;
- shallower modelled units than expected in the Motherwell-Lanarkshire area;
- Inch of Ferryton well, Stratheden Group data point not fitted (Section 2.3, Appendix 1)

The H_{rec} values incorporate a range of standard values and assumptions (e.g. Rollin et al. (1995), Piris et al. (2021), Veldkamp et al. (2021)) and are described as tentative; alternative methods to calculate heat recoverable (e.g. Doubletcalc, including a flow rate) are likely to prove valuable for specific sites, where input parameters may be better known.

The temperature gradients have been corrected for the time since circulation but not a paleoclimate correction, such as in Watson (2022) who suggested a resultant increase in the heat flux by c. 20 W/m^2 in some areas. Such a correction should be included in future work.

7 Discussion and conclusions

A first regional-scale estimation of the ‘hot sedimentary aquifer’ (or ‘hydrothermal’) Heat-In-Place for the potential geothermal energy source of sandstone-dominated strata of central Scotland has been made. The modelled extents and estimation of the potential resource are provided with high uncertainty due to the data quantity and quality for the Upper Devonian Kinnesswood Formation and Stratheden Group target, where buried at several kilometres depth. Uncertainties range from the presence and thickness of the units to their porosity, permeability and temperature.

This estimation represents a starting point for more detailed analysis and interpretations, highlighting potential opportunities from 44–166°C at depths of up to 6 km. An upper 1.4 km relative to Ordnance Datum depth cut-off representing the depth at which the temperatures averages 50°C is used to assess the resource potential for direct use of heat. Using the heat calculator of Piris et al. (2021), the modelled results are P10 = 361.1 EJ, P50 = 341.7 EJ, P90 = 312.5 EJ for Heat-In-Place and tentatively P10 = 51.4 GW, P50 = 35.6 GW, P90 = 23.2 GW for modelled heat recoverable. The values are decreased by approximately a third by removing areas further than 1 km offshore in the Firth of Forth for which the heat demand and techno-economics would be significantly different. Resultant Heat-In-Place values for onshore and within 1km of the coastline are P10 = 257.8 EJ, P50 = 243.9 EJ and P90 = 223.1 EJ and P10 = 36.7 GW, P50 = 25.4 GW and P90 = 16.6 GW for modelled recoverable heat.

After establishing the presence and thickness of the target geothermal reservoir, the achievable and sustainable flow rate is a key parameter for a potential hot sedimentary aquifer estimation. Aquifer properties of the Kinnesswood Formation and Stratheden Group target have been incorporated from measured data, however the known variability within the stratigraphical units has not been modelled. A key uncertainty to the geothermal potential across the Midland Valley of Scotland remains whether the aquifer properties deteriorate at depths greater than 500 m.

Despite the high geological uncertainty, the hot sedimentary aquifer presents significant opportunity for a decentralised heat supply in central Scotland, coincident with some major population centres including Stirling, Glasgow, Falkirk and Dunfermline. Compared to other UK geothermal opportunities (e.g. Permo-Triassic sandstones: 8 EJ Worcester Basin, 122 EJ Eastern England in Abesser et al. 2023) the Heat-In-Place values are large due to the greater depth and unit thickness combined with moderate porosity values, though the geological uncertainty is higher. The tentative values of heat recoverable ranging from *c.* 2–33MW/km^2 under cities are of similar magnitude to the heat demand shown on Scotland’s heat map (Scottish Government, 2024).

Sandstone-dominated units of Strathmore (Lower Devonian), Moray and Caithness (Devonian), the Borders (Upper Devonian) and Dumfries and Galloway (Permian) forming moderate, high and very high productivity aquifer units at outcrop and shallow subsurface across Scotland also form potential aquifer geothermal opportunities. They have not been assessed during this study due to lack of subsurface data. The Passage Formation high productivity aquifer (Carboniferous) was included in this model and assessment but with maximum burial depths of around 1 km onshore (corresponding to maximum estimated temperatures of around 34°C), this unit will be considered further in a separate analysis of the shallower, lower temperature geothermal energy source for open loop ground source heat systems, along with the shallower parts of the Upper Devonian strata modelled here.

Ultimately, deep geothermal wells need to be drilled to de-risk the Upper Devonian sandstone target.

Glossary

Aquifer: underground layers of water-bearing, permeable rocks that contain and transmit groundwater and from which groundwater can be extracted.

Boreholes: deep, narrow holes made in the ground, either vertically or inclined, often to locate water or oil.

Conversion efficiency: Factor that considers the heat exchange efficiency from the geothermal fluid to a secondary fluid in a thermal plant.

Deep geothermal: term used widely to refer to systems at a depth of more than 500 m below the surface. In this document, the term is used to mean system that produce heat in the 50–200°C range of medium temperature (steam or water). This may be regarded as medium-high grade heat, suitable for multiple uses including direct use for space heating, industrial and horticulture use or power generation.

Direct-use geothermal: a system that is hot enough for geothermal heat to be used directly (for example for district heating) without requiring an electrical heat pump.

District Heating: communal heating systems that deliver heated water to a large number of homes and buildings via a heat network.

Exajoule (EJ): a unit of energy equal to one trillion (10^{18}) joules.

Geothermal reservoirs: underground zones of porous or fractured rock that contain hot water and/or steam. They can be naturally occurring or human-made.

Geothermal resource as used in Rollin et al. 1995: total Heat-In-Place within an aquifer

Gigajoules (GJ): a unit of energy equal to one thousand million (10^9) joules.

Gigawatt (GJ): a unit of power equal to one thousand million (10^9) watts.

Groundwater: water that exists in pores and fractures in the rocks and soils beneath the land surface where it forms saturated zones (aquifers).

Heat exchanger: a device for transferring heat from one fluid to another, or for transferring heat to or from the ground.

Hot sedimentary aquifers: see hydrothermal systems.

Heat pump: a device that transfers and "upgrades" heat from a colder space to a warmer space using mechanical energy. There are three main types of heat pump: ground source, air source and water source. The name of each one describes where the appliance takes its heat from. A heat pump can also function as an air conditioner to provide space cooling.

Hydrothermal systems: (also referred to as "hot sedimentary aquifers"): geothermal systems that contain fluid, heat and permeability in a naturally occurring geological formation or sedimentary basin for the production of heat or electricity.

Identified resource as used in Rollin et al. 1995: Part of the geothermal resource that may be available for development

Igneous (or magmatic) rocks: rocks formed through the cooling and hardening of molten rock (magma). A body of magma that cools and hardens below the surface is called an **igneous intrusion**.

Joule (J): the standard unit of energy. One joule is equivalent to the energy released as heat when an electrical current of one ampere passes through a resistance of one ohm for one second. One joule equals one watt-second or 0.00028 watt-hours.

Kilowatt (kW): a unit of power equal to one thousand (10^3) watts.

Kilowatt-hour (kWh): a unit of energy equal to one thousand (10^3) watt-hours.

mOD: meters relative to Ordnance Datum (see level)

Megajoules (MJ): a unit of energy equal to one million (10^6) joules.

Megawatt (MW): a unit of power equal to one million (10^6) watts.

Open-loop GSHP system: a geothermal system that typically pumps warm groundwater directly from an aquifer or flooded mine system via a production borehole and, after heat extraction, returns the cooled water to the system via an injection borehole (see also geothermal doublet).

Permeability: a measure of whether and how fast water can flow through a rock.

Petajoule (PJ): a unit of energy equal to one thousand billion (10^{15}) joules.

Resource (according to UNFC-19): the cumulative quantities of geothermal energy that will be extracted from the available geothermal energy source. The term is only applicable to areas where the existence of a significant recoverable geothermal energy has been proven (i.e. Known Geothermal Sources).

Sedimentary basins: low areas in the Earth's crust, of tectonic origin, in which thick deposits of sediments accumulate over geological time periods.

Technical potential (Beardsmore protocol): the fraction of the physically accessible potential (see theoretical potential) that can be used under the existing technical, structural and ecological restrictions as well as legal and regulatory allowances.

Theoretical potential (Beardsmore protocol): the theoretically realizable energy supply considering only physical constraints (i.e. the physically-usable energy supply) (for comparison see technical potential)

Watt (W): a unit of power - the rate at which energy is transferred or converted.

Watt-hour (Wh): a unit of energy equivalent to using one watt of electricity for one hour. One watt-hour is equal to 3,600 joules.

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Appendix 1 – Geological interpretation, caveats and limitations

Borehole/well interpretations

The few wells across central Scotland that penetrate the potential Kinnesswood Formation-Stratheden Group target aquifer at depths greater than 1 km prove sequences not as easily recognisable as those mapped at or near surface. A variety of interpretations results (Table 9), which influence the potential geothermal estimation. The timeline of interpretations is commonly:

- Original composite well logs provide a lithostratigraphical interpretation that may include paleontological analysis in addition to recognisable stratigraphical characteristics.
- For deep wells drilled between the 1980's and early 2000's, BGS geologists with extensive regional experience were generally present for logging or examined materials close to the time of drilling; further palynological or petrological analysis was also undertaken. *These interpretations are used in this study.*
- Subsequently, others have provided alternative interpretations, with varying degree of new analysis or additional constraining data.

Table 9 Examples of alternative interpretations for two key wells penetrating the Kinnesswood Formation, Stratheden Group.

Well	Composite log stratigraphical interpretation	BGS updated interpretation (in Monaghan 2014; Appendix C)	Other interpretations
Salsburgh 1A	Standard sedimentary sequence to Burdiehouse Limestone, volcanic rocks undefined and Lower Old Red Sandstone trachyte at base	As in BGS Falkirk Memoir (Cameron et al. 1998), but with the interpretation of Devonian microgranodiorite intrusion at base of well after Phillips & Browne (2000) petrology study, beneath the Salsburgh Volcanic Formation and missing lower Carboniferous and upper Devonian succession	Watson (2022) interprets Stratheden Group below the igneous rocks at the base of the well, shown on a cross-section (his fig. 2.11 pg32)
Inch of Ferryton 1	Biostratigraphy report (Robertson Research 1986) confirms ages to Visean, upper Asbian NM-VF zone in the Strathclyde Group at deepest 6128 ft (1867 m) No palynology judged in situ beneath this Inverclyde Group 6360-6520 feet – petrographic and well log evidence, allied to Ballagan Fm facies. Stratheden Group from 6520 feet including red-purple-brown breccia/tuffaceous claystone/sandstone from 6800 feet. Noted igneous and metamorphic components - breccia unit may be Gargunnock Sandstones?	Interpretation taken from an unpublished BGS petrology report on cuttings, the Robertson Research 1986 biostratigraphy report, and lithologies - to include Pathhead Formation between 5,663 - 5,898 ft and to correlate the Strathclyde Group (5,898 - 6,360 ft) with the Sandy Craig Formation. Strata from 6,800 to 7,800 ft dominated by volcanic rocks from thin section and point counting analysis (Phillips and Browne 2001, unpublished), interpreted as Devonian in age. Stratheden Group with significant mudstone component from 6520–6760 ft (1987–2060 m; 73 m thick) and dominantly igneous rocks beneath.	Heinemann et al. (2018) interpreted section beneath 6800 feet as Kinnesswood Fm and Stratheden Group conglomerate with 'high quality well sorted sandstones deposited in aeolian and fluvial environments' Henry (2019) – small diagram roughly as per composite log (minor depth difference) Williams (2022) Carboniferous (Visean) interpretation in the bottom section of the well with Lawmuir Fm to 2060 m (6769 ft) and Clyde Plateau Volcanic Fm beneath.

Constraining the extent, thickness and depth variations of key aquifer units

The thickness of the potential aquifer units is a sensitive variable for the Heat-In-Place calculation. Due to limited amount and poor quality of deep (> 1-2 km) subsurface data, the thickness of the Kinnesswood Formation and Stratheden Group is poorly known across the deep parts of the subsurface basins:

- The variable thickness of Kinnesswood Formation (200-600 m) is evident from surface exposures and depth maps in Browne et al. (1985, 1999). There are few borehole/well penetrations at depth but interpretation of seismic and geophysical data, combined with 3D geological model interpretations on overlying intervals help to constrain the 3D model depth and thickness for this study (Section 3).
- The distribution of the Stratheden Group and component Knox Pulpit Formation is uncertain. Browne at al. (1985) provided a contour map with the Stratheden Group present on the northern side of the Midland Valley only, excepting a small area south of Ayr where it is present at outcrop. The dataset has not markedly changed since that time, though there is (i) mapping of undifferentiated Stratheden Group-Inverclyde Group on the south-eastern side of the MVS between the Dunbar-Gifford and Lammermuir Faults and at Cove in the Dunbar-Oldhamstocks Basin (BGS 1:50,000 maps) and (ii) seismic interpretation that places the Inch of Ferryton below the top Inverclyde Group in the footwall block of a fault structure (Monaghan 2014 page 30) i.e. a relative local high with a condensed or partially missing section of the Stratheden Group. (iii) interpretation of a local gravity and modelling study from Watson (2022) in eastern Glasgow with 150 m of Kinnesswood Formation and 150 m of Stratheden Group, with top Kinnesswood interpreted to be buried between at depths around 1.4 km or 1.7 km depending on model scenario.
- As a result of the regional scale of this work, the geological model utilises the Stratheden Group contours from Browne et al. (1985). It is not possible to reconcile the interpretation of the depth and thickness of the Stratheden Group in the Inch of Ferryton well in this study, due to the modelled resolution excluding smaller faults from the model, resulting in mismatch between this well data point and the geological model (Section 3).

The output for the Kinnesswood Formation-Stratheden Group aquifer units show an area of non-deposition in the Salsburgh-Airdrie-Bathgate area (Figure 5). This area has been input in the geological model. A larger area of non-deposition was included in Browne et al. (1985) paleogeography map for the Upper Devonian (Knox Pulpit Formation) and is evidenced by:

- The interpretation of the Salsburgh 1A well as penetrating from the Carboniferous Salsburgh Volcanic Formation to a Devonian microgranodioritic intrusive body (Phillips and Browne 2000) with no intervening Carboniferous or Devonian sedimentary units (Table 12).
- A significant magnetic anomaly ‘Bathgate anomaly’ which has been interpreted as a major intrusive body or as a thick pile of volcanic rocks buried beneath the sedimentary sequence (Rollin 1987; 2009; Bathgate and Arran profile lines)
- Seismic reflection data is challenging to interpret for the strata beneath the Clyde Plateau Volcanic Formation (e.g. Penn, Smith, and Holloway (1984) discuss lines to the north-east of the area of non-deposition), with limited or no well control.

The extent, thickness and depth of the Upper Devonian units has high uncertainty. Features such as the interpreted area of non-deposition have significant impact on the geothermal estimation.