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UKGEOS - Glasgow Geothermal Energy Research Field Site (GGERFS): Initial summary of the geological platform

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UKGEOS - Glasgow geothermal Energy Research Field Site (GGERFS): Initial summary of the geological platform

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Summary

The preferred second UKGEOS site is at Clyde Gateway, in the east end of Glasgow, Scotland. The focus of this, the Glasgow Geothermal Energy Research Field Site (GGERFS), is on characterising and monitoring the subsurface for minewater and hot sedimentary aquifer geothermal energy, and for cooling and heat storage.

This report details BGS data and knowledge **at late 2016**, to define initial characterisation of the 'geological platform' relevant for the planning of a geothermal research facility and associated environmental baseline monitoring. The report covers knowledge of the bedrock and superficial deposits geology, abandoned coal mines, hydrogeology, geothermal datasets, geochemistry, remote sensed data, seismicity, stress fields, engineering geology and rock property datasets.

BGS holds a great deal of legacy borehole, mining and geochemistry data and has updated existing bedrock and superficial deposits models of the area. However, deep borehole and seismic data are lacking to define the geology and structure of the area below a few hundred metres. Hydrogeological and temperature data are also lacking for the bedrock strata. Regional datasets and knowledge have (and can be further) used to reduce uncertainty and risk in these aspects of the geological characterisation.

1 Introduction

1.1 BACKGROUND

The BGS and the Natural Environment Research Council (NERC) have developed plans for delivering the UKGEOS project (formerly the Energy Security & Innovation Observing System for the Subsurface (ESIOS) project) which will establish new centres for research into the subsurface environment. The knowledge they generate will contribute to the responsible development of new low-carbon energy technologies both in the UK and internationally. The UKGEOS (ESIOS) work is steered by a Science Plan.

The capital project is NERC's response to the Government's announcement in the 2014 Autumn Statement that it would allocate £31m to create world-class subsurface energy research test centres through NERC, operated by the British Geological Survey (BGS). The first facility is planned for the west Cheshire area and will focus primarily on observations of fluid flow and geomechanical processes in the subsurface associated with development of unconventional energy resources and aquifers (see http://www.bgs.ac.uk/research/energy/esios/cheshire/home.html; Hough et al., 2016). Following discussions with the then ESIOS Scientific Advisory Group and as agreed by the then ESIOS Project Board, the second site – to be called the Glasgow Geothermal Energy Research Field Site (GGERFS), is planned for the Clyde Gateway area in Scotland, focusing on geothermal energy. Specifically,

(i) relatively shallow (few hundred metres) minewater geothermal potential

(ii) deeper (1–2 km) hot sedimentary aquifer geothermal potential

(iii) potential for heat storage and sub-surface heat transfer

This report details the state of BGS knowledge - at late 2016 - contributing to the 'geological platform', relevant for the planning of a geothermal research facility and associated environmental baseline monitoring at GGERFS in the Clyde Gateway area. This initial summary was completed by BGS ahead of any formal announcement by NERC and as such stakeholders did not provide any input to this document. This is an initial summary; going forward, the geological platform etc. will develop and stakeholder involvement will grow and diversify.

1.2 THE CLYDE GATEWAY AREA

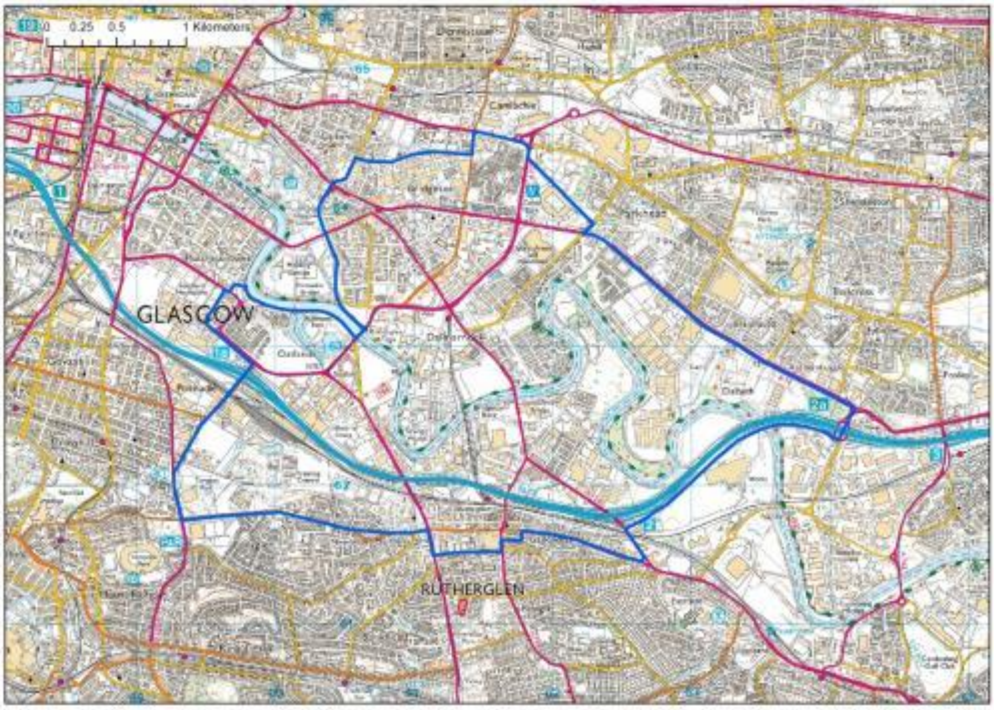


Figure 1 Clyde Gateway area – blue outline (Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2018. Licence number 100021290 EUL)

The area of interest for GGERFS is in the Clyde Gateway, located in the East End of Glasgow (Dalmarnock) and Rutherglen, and straddling the boundary between Glasgow City and South Lanarkshire councils on the north and south sides of the River Clyde (Figure 1). Clyde Gateway is an urban regeneration area, of c.840 hectares, comprising newly built sports facilities and housing for the 2014 Commonwealth Games, some pre-existing 19th and 20th century legacy housing, and vacant and derelict land with a history of multiple former industrial uses and housing. Some of area is owned by Clyde Gateway URC (Urban Regeneration Company; a partnership of Glasgow City Council, South Lanarkshire Council and Scottish Enterprise, backed by Scottish Government). Some individual blocks of land have been acquired by private developers.

The focus for this report is the Clyde Gateway area.

1.3 SUMMARY OF GEOLOGY AND PREVIOUS BGS WORK

The Clyde Gateway area is underlain by a complex glacial and post-glacial superficial deposits succession up to *c*.35 m thick, including substantial anthropogenic deposits, of varying lithology and engineering properties. The bedrock geology is a faulted, heterolithic coal-bearing sequence that has been extensively mined to depths of approximately 270 m. The site is typical of the complex geology found in many UK coalfields and as such forms a realistic exemplar for study as a subsurface monitoring laboratory.

BGS has worked in the Glasgow area for many years with extensive data collection, digitisation, interpretation and modelling undertaken from 2005–2012 as part of co-funded work with Glasgow City Council, Clyde Gateway URC and others in the Clyde-Urban Super-Project (CUSP). The scope of this work ranged from geology, hydrogeology and engineering geology to soil and water geochemistry (e.g. Merritt et al., 2007; Campbell et al., 2008; Fordyce, 2012; Monaghan et al., 2014). Thus, a range of surface and subsurface data have already been collected, digitised and interpreted, for example:

- 1:10k digital geological and environmental geology maps,
- 3D geological models for superficial deposits and bedrock
- extensive shallow (top 30 m) borehole database with more limited deeper borehole records
- extensive digitised mine abandonment plans
- urban soil survey and stream sediment data
- groundwater monitoring data and conceptual groundwater models for superficial deposits

The majority of the information is publically available, with models being accessed through the ASK Network. Work is currently underway to resolve confidentiality constraints for some data and information BGS holds for the Clyde Gateway area, such that a consistent package of Open data or third party data owner details will be available to external users.

1.4 INITIAL EXAMPLES OF SCIENCE QUESTIONS AT "ESIOS CLYDE" IN THE CLYDE GATEWAY AREA

A number of initial science questions were outlined during the selection process for the then "ESIOS" second site in the Clyde Gateway area. These included:

Mine water geothermal

- Measuring/monitoring of minewater flow in a complex system of multiple mined seams, in a complex, faulted succession
- Do faults act as barriers or conduits for flow?
- How far does pumping/heat extraction at one site influence heat and fluid flow at another site?

Hot sedimentary aquifer geothermal

- Are sandstone aquifers – hot enough, permeable enough, have enough volume for continued geothermal supply?
- Role of mudstones etc and other seals in compartmentalising the resource and influence on resource potential.
- Role of faults and other discontinuities as barriers or conduits to flow.

General

- Monitoring to address complexities of the geothermal gradient in a substantially anthropogenically-influenced groundwater environment
- Potential for heat storage and heat transfer
- Potential for linkage of any heat resource to a developing District Heating Network

2 Bedrock Geology

2.1 OVERVIEW

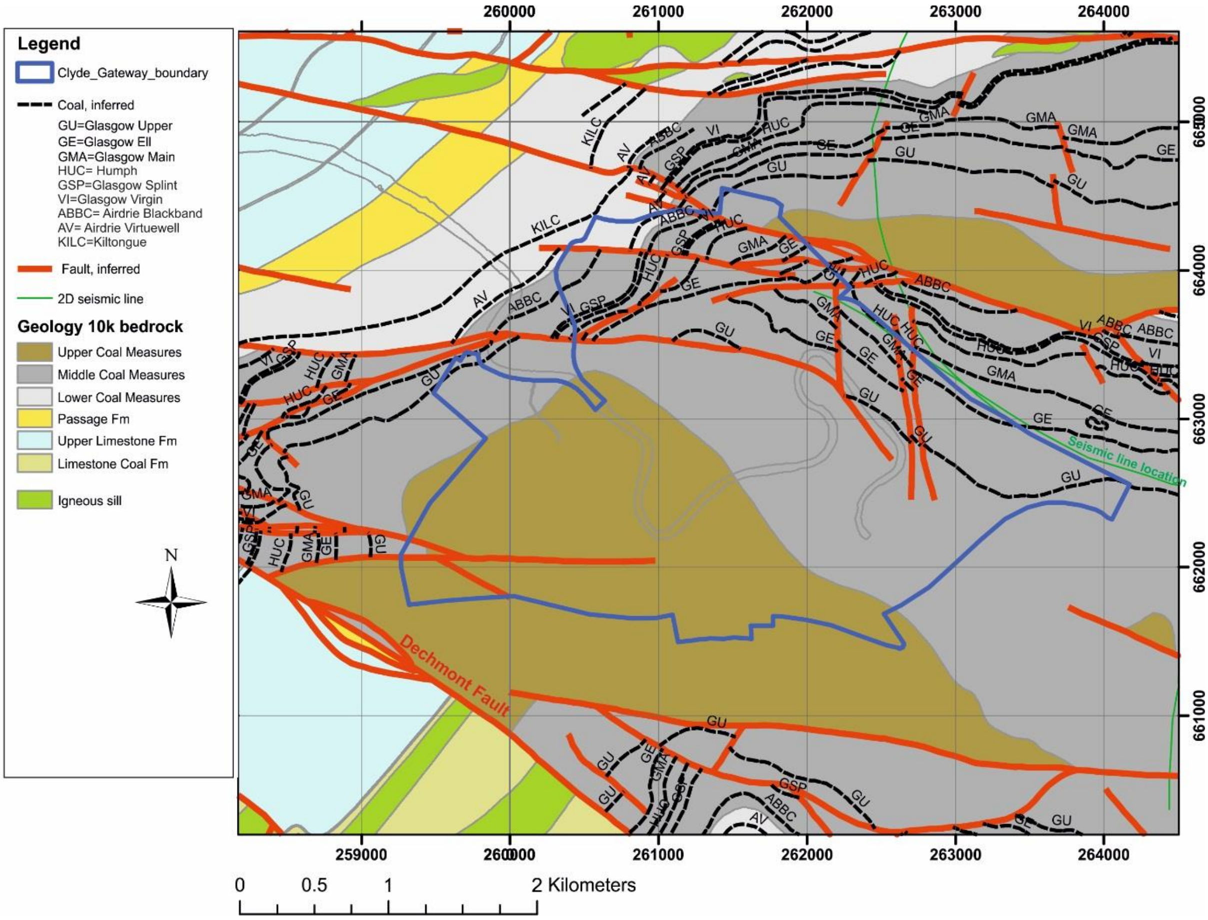


Figure 2 Clyde Gateway area summary of bedrock geology from BGS©NERC 2016 DigMapGB 1:10 000 scale data.

The bedrock strata beneath the Clyde Gateway area comprise proved Carboniferous sedimentary rocks of the Scottish Upper, Middle and Lower Coal Measures, Passage and Upper Limestone formations (Figure 2). Based on the surrounding geology and deeper boreholes within a few kilometres of the study area, older Carboniferous strata of the Limestone Coal and Lower Limestone formations (Clackmannan Group) are expected at depths of around 500–1600 m (Figures 3, 4). These successions are dominantly fluvio-deltaic to shallow marine cyclic mudstones, siltstones, sandstones, coals and limestones.

At deeper levels, the geological sequence is poorly constrained with strata of the West Lothian Oil-Shale Formation or the laterally equivalent Lawmuir Formation predicted to lie above the Kirkwood and Clyde Plateau Volcanic formations. The early Carboniferous Clyde Sandstone, Ballagan and Kinnesswood formations underlie the volcanic rocks to the north and south of Glasgow and would be predicted beneath the Clyde Plateau Volcanic Formation (Figure 3).

Potential geothermal resources are situated within the extensive abandoned flooded coal mine system of the Scottish Middle and Lower Coal Measures formations, with tunnels, shafts and workings across the entire eastern Glasgow conurbation as far as Wishaw (Campbell et al. 2010; Gillespie et al., 2013, , Kearsey et al., in press).

Potential hot sedimentary aquifer geothermal resources have been considered within the sandstone-dominated Passage Formation in the wider Glasgow and central Scotland area (Browne et al., 1985; Hall et al., 1998), though temperatures linked to relatively shallow burial depths were a concern. Multiple channelised sandstones in the Upper Limestone, Limestone Coal and Lower Limestone formations are known in the wider Glasgow area. Deeper, lower Carboniferous-upper Devonian sandstones (potentially at depths of 2 km or more) beneath the Clyde Plateau Volcanic Formation were identified as geothermal targets by Browne et al (1985) but lack of data precludes any knowledge of their presence or character at depth in the vicinity of Clyde Gateway.

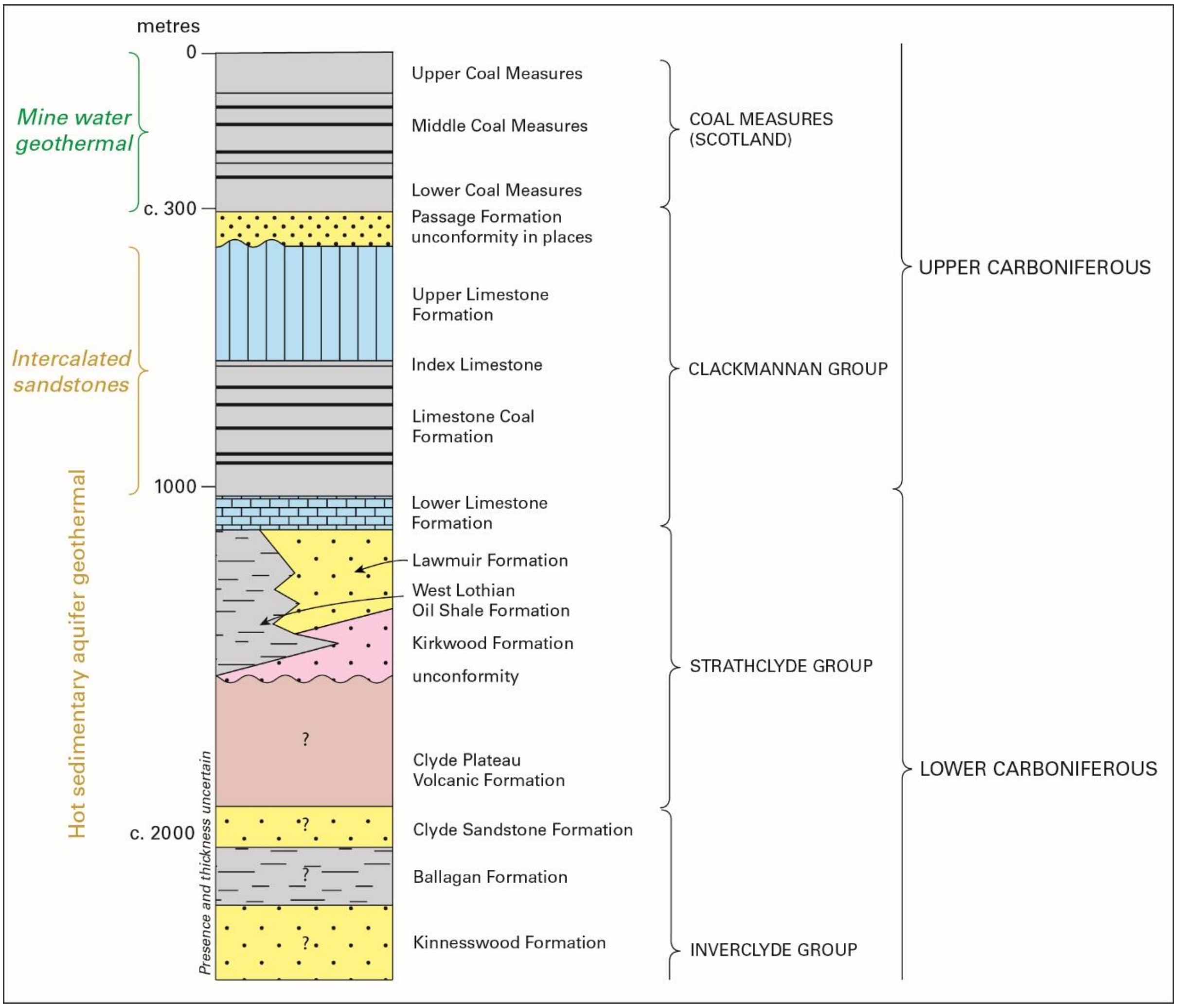


Figure 3 Summary of proved and possible lithology and stratigraphy in the Clyde Gateway area. Possible intervals for consideration of geothermal potential indicated.

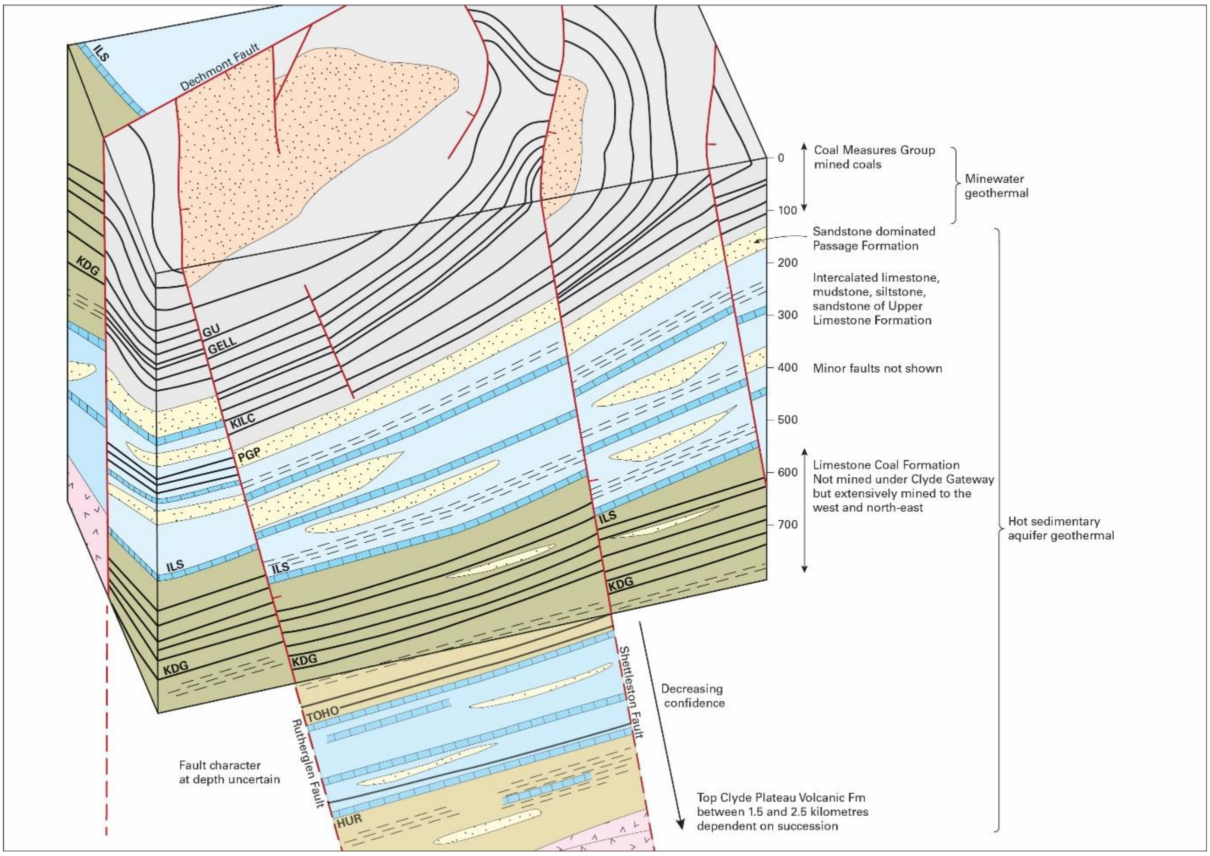


Figure 4 Visualisation of possible geology and geothermal targets beneath the Clyde Gateway area. Geology within the cube based on 3D bedrock model. ILS=Index Limestone, KDG= Knightswood Gas Coal, GU= Glasgow Upper Coal, GELL= Glasgow Ell Coal, KILC=Kiltongue Coal, PGP=Passage Formation, TOHO=Top Hosie Limestone, HUR=Hurlet Limestone.

2.1.1 Bedrock faulting and structure

Complex faulting, comprising mainly steep faults, pervades the area. 45 faults on a variety of trends have been modelled in the current bedrock model of the 10 km by 10 km area which contains the Clyde Gateway area (Monaghan et al., 2014). The sedimentary rocks are cut by Late Carboniferous igneous intrusive sills and are also folded. The most common larger faults are roughly E-W-trending (Figure 2). The major Dechmont Fault trends north-west and downthrows Coal Measures to the north-east against Clackmannan Group strata. There is a major easterly-plunging, E-W-striking open fold of Coal Measures strata in the hanging wall of the Dechmont and Rutherglen faults; this structure covers the southern part of the Clyde Gateway area. Clackmannan Group strata are folded into c.north-north-east- to north-east-trending synclines and anticlines in areas surrounding the Clyde Gateway area. All areas are cut by north-west- to east-north-east-trending faults.

The Dechmont Fault (Figure 2, 4) has been interpreted as a deep and long-lived north-west-trending lineament (Forsyth et al., 1996; Hall et al., 1998). It divides two Midland Valley Upper Carboniferous structural styles – a north-east-trending half-graben/graben block and basin to the west (Ayrshire) and north-north-east-trending growth folds to the east (Central Coalfield and Fife; Hall et al., 1998). Strike-slip to extensional tectonism was active during the Carboniferous (Forsyth et al., 1996; Hall et al., 1998; Read et al., 2002; Underhill et al., 2008), so stratal thickening and thinning across fault and fold structures is expected.

2.2 DATASETS

2.2.1 Boreholes

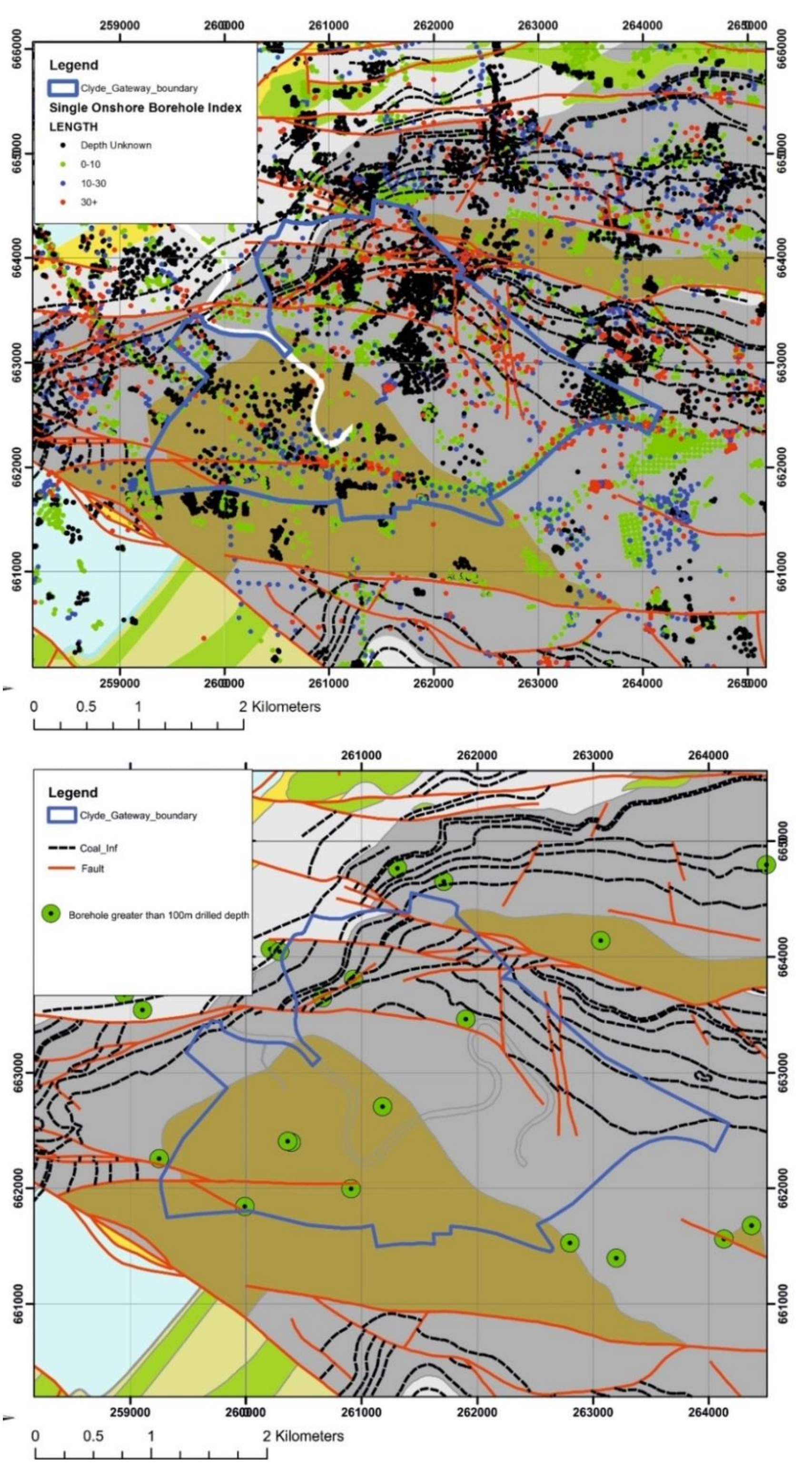


Figure 5 All boreholes held in the BGS SOBI database (above). Boreholes greater than 100 m drilled depth (below). Clyde Gateway area in blue. Key to geology map on Figure 2

BGS holds over 3,400 borehole records within the Clyde Gateway area (Figure 5 above). However the majority of these penetrate to depths of less than 30 m beneath the ground surface, with only ten borehole records having a drilled length greater than 100 m (Figure 5 below).

The abundant borehole records adequately constrain the geology of the superficial deposits, and provide important information concerning the position of unmined and mined coal seams close to rockhead in the northern half of the Clyde Gateway area. Mined coal seams are commonly encountered in boreholes as ‘waste’ (collapsed workings) or occasionally as open ‘voids’.

The BGS.SOBI and BGS.Borehole_Geology databases were updated in autumn 2016 with borehole records received since the previous phases of work in 2009 and 2011. Updated borehole interpretations were fed into revised versions of the bedrock and superficial deposits models (see below).

2.2.2 Hydrocarbon wells and geophysical well logs

Limited geophysical well log data is available, all from outside the Clyde Gateway area (Figure 6). Three IGS (BGS) wells drilled at Maryhill (1983, 306 m, Limestone Coal and Lower Limestone formations), Alexandra Parade (1976, 222 m, Scottish Lower Coal Measures, Passage, and Upper Limestone formations) and Hallside (1976; 348 m; Scottish Upper and Middle Coal Measures formations) recorded a mixture of gamma, density, SP, resistivity, temperature, caliper logs. The Bargeddie 1 hydrocarbon exploration well (1989, 1046 m, Scottish Coal Measures to West Lothian Oil-Shale formations) has a large suite of geophysical logs (Teredo, 1989), plus some Rock-Eval source rock analysis (Monaghan, 2014 Appendix D). Gas shows within sandstones of the West Lothian Oil-Shale Formation showed initially promising pressures and estimated volumes but further fracturing and pressure testing showed a decline in reservoir pressure, suggesting a ‘small bounded reservoir model’ (1989 well report, Teredo and Oilfeld Production Consultants).

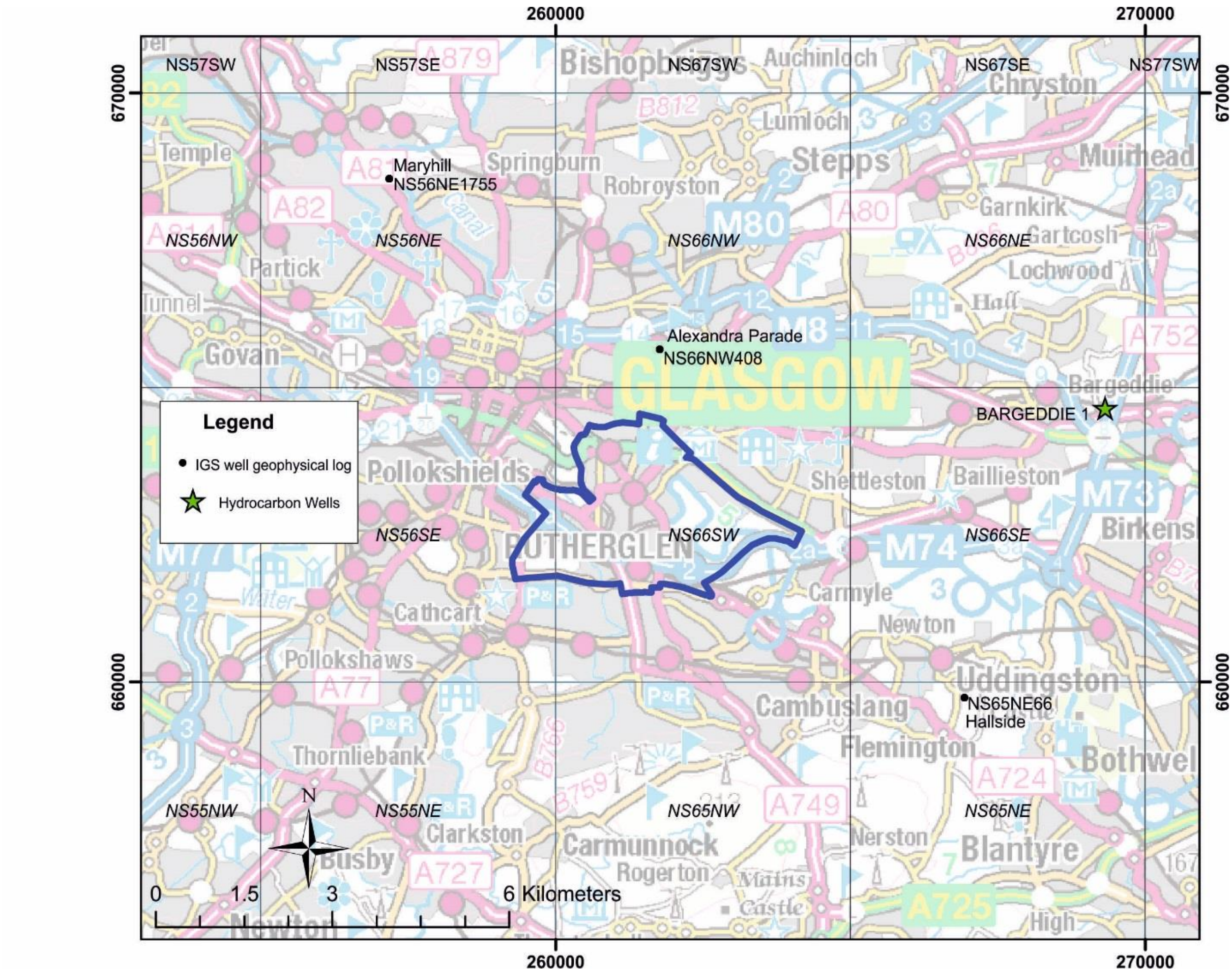


Figure 6 Location of the three IGS (BGS) boreholes with geophysical well logs in the wider Glasgow area, and the Bargeddie 1 conventional hydrocarbon exploration well. Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2017. Licence number 100021290 EUL

2.2.3 Mine abandonment plan data

There are historical mine workings for coal in eight seams beneath a large part of the Clyde Gateway area, and related shafts and interconnecting underground roadways (Figure 7).

No records of mine workings for materials other than coal (ironstone etc) within the Clyde Gateway area have been located. .

Workings recorded in coal mine abandonment plans dating from 1810–1934 have been captured by BGS for the following seams:

- Glasgow Upper Coal (Scottish Middle Coal Measures Formation)
- Glasgow Ell Coal (Scottish Middle Coal Measures Formation)
- Glasgow Main Coal (Scottish Middle Coal Measures Formation)
- Humph Coal (Scottish Middle Coal Measures Formation)
- Glasgow Splint Coal (Scottish Middle Coal Measures Formation)
- Glasgow Virgin Coal (Scottish Middle Coal Measures Formation)
- Airdrie Virtuewell Coal (Scottish Lower Coal Measures Formation)
- Kiltongue Coal (Scottish Lower Coal Measures Formation)

Extents of all mined areas, including sub-areas of stoop and room workings, have been digitised to GIS from the abandonment plans (Figure 7), as have spot heights, contours, shafts and roadways. Faults have been extracted from plans where marked and proved, and/or interpreted from offsets in spot height or contour data, combined with gaps in worked panels. Areas of probable workings have been interpreted where there is no mine abandonment plan record but where workings have been proved in boreholes as ‘waste’ or ‘voids’.

The deepest mineworkings in the area are shown on the plan of the Kiltongue Coal (Lower Coal Measures) as recorded at depths of -268.5 m. The depths marked on mine plans were surveyed in, and are believed to be accurate to within a metre or less. Accuracy will decrease with distance from a shaft. If underlying seams were mined subsequently to a particular plan, then the depths on the older plan may have been affected by subsidence from younger, underlying workings. This cumulative subsidence may need to be taken into account at a site specific level for borehole planning purposes.

The abandoned, flooded mine workings form the resource for ‘shallow’ geothermal heat and heat storage (Gillespie et al., 2013). Roadways emanating from shafts may be of particular importance as they are believed to be open at the present time, greatly increasing permeability and potential yield (Gillespie et al., 2013).

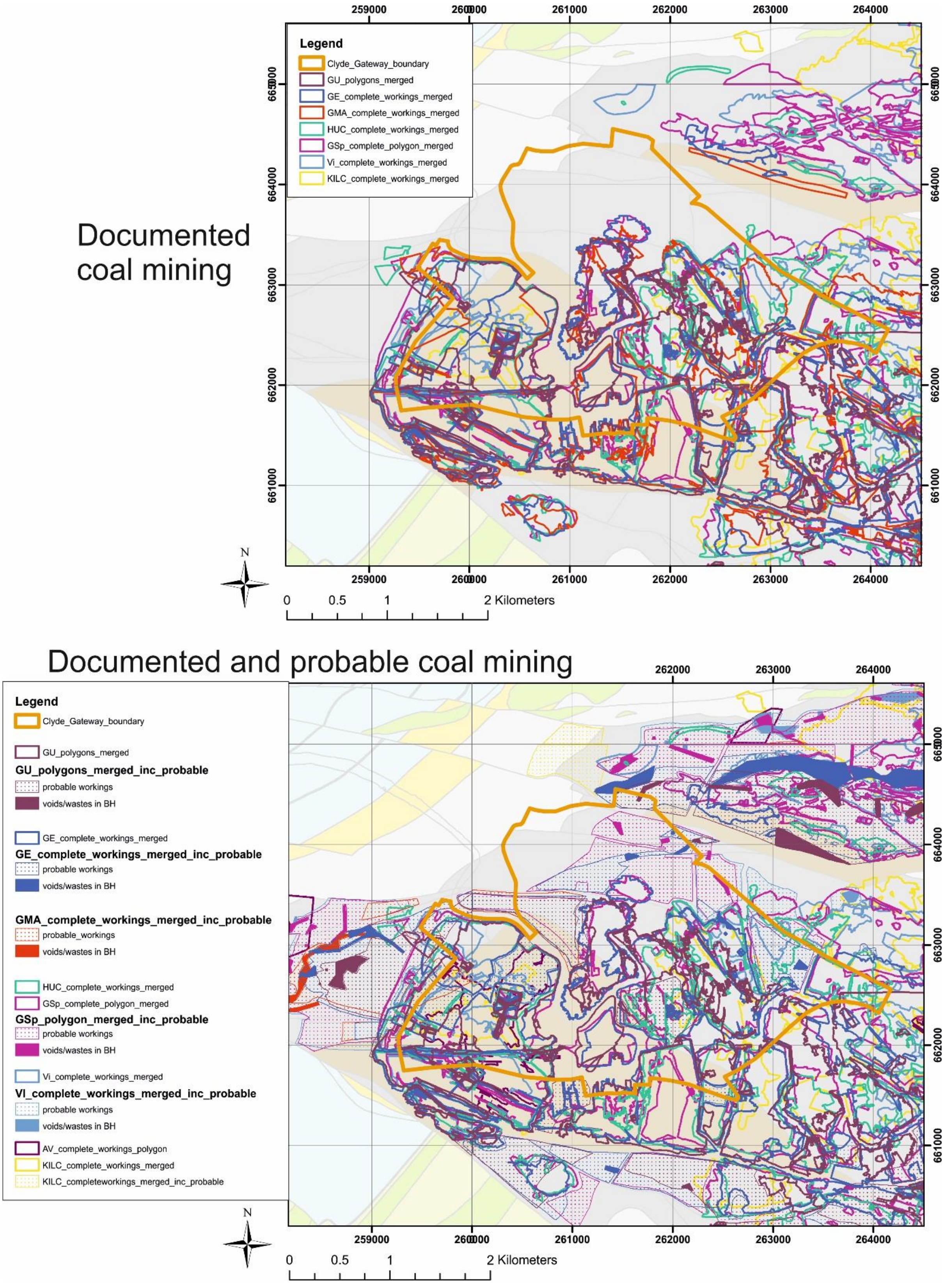


Figure 7 Summary of known (above) and probable (below) mining extents BGS©NERC 2016 for the Clyde Gateway area.

2.2.3.1 THE COAL AUTHORITY DATASETS

The Coal Authority is the definitive source of coal mining information in the UK. Some datasets are openly available on its website, such as the position of shafts and mine entries, and areas of known and probable shallow mining (Figure 8, and see http://mapapps2.bgs.ac.uk/coalauthority/home.html). GIS versions of mine plan datasets can also be licensed (see https://www.gov.uk/guidance/coal-mining-records-data-deeds-and-documents).

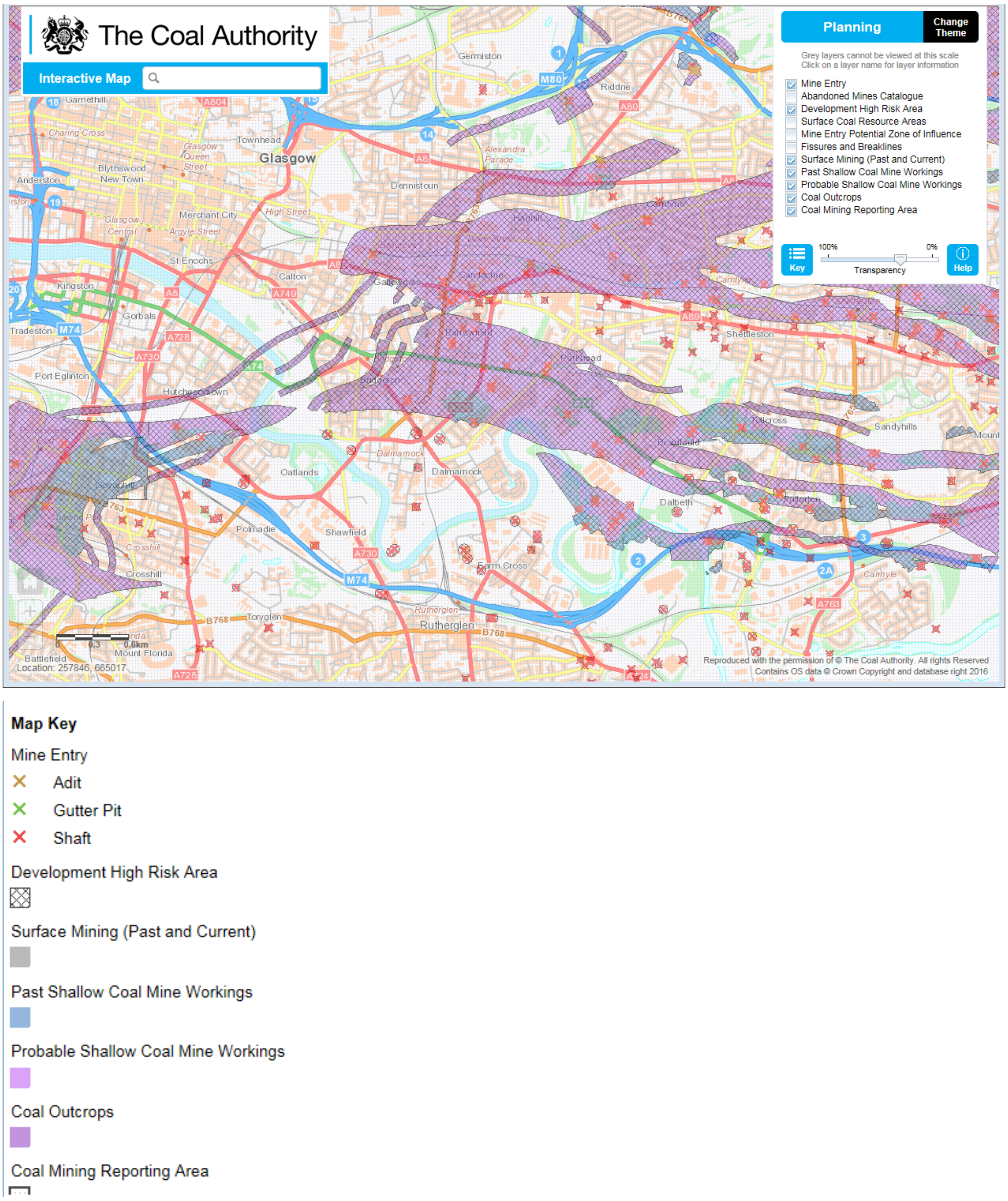


Figure 8 Screenshot of The Coal Authority interactive viewer for eastern Glasgow highlighting the probable shallow coal mine workings in the north and east of the Clyde Gateway area.

Additional coal mine datasets (e.g. mine discharges, hydrogeochemistry, coal properties) may be held in the archives of The Coal Authority and BGS. Future work will investigate this further.

2.2.4 Legacy 2D seismic data interpretation

2.2.4.1 INTRODUCTION

A set of legacy 2D seismic lines from a 1985 survey located adjacent to the proposed Clyde Gateway area were interpreted with a view to: integrating the information into the Clyde Gateway geological platform; and through this gain a greater understanding of the subsurface in the area. The depth converted seismic horizons were imported into an existing 3D model to help constrain the surfaces. One deep commercial exploration well, Bargeddie 1, was used to tie the seismic reflectors; the well is 190 m off the nearest seismic profile. Velocity data from the well were used to obtain a velocity/ depth relationship and to depth convert the seismic events.

2.2.4.2 LOCATION AND DATASET

There are no seismic profiles within the Clyde Gateway area but a series of profiles with spacings of >1 km to >3 km and general north–south, east–west orientation are located east and north-east of the project area (Figure 9).

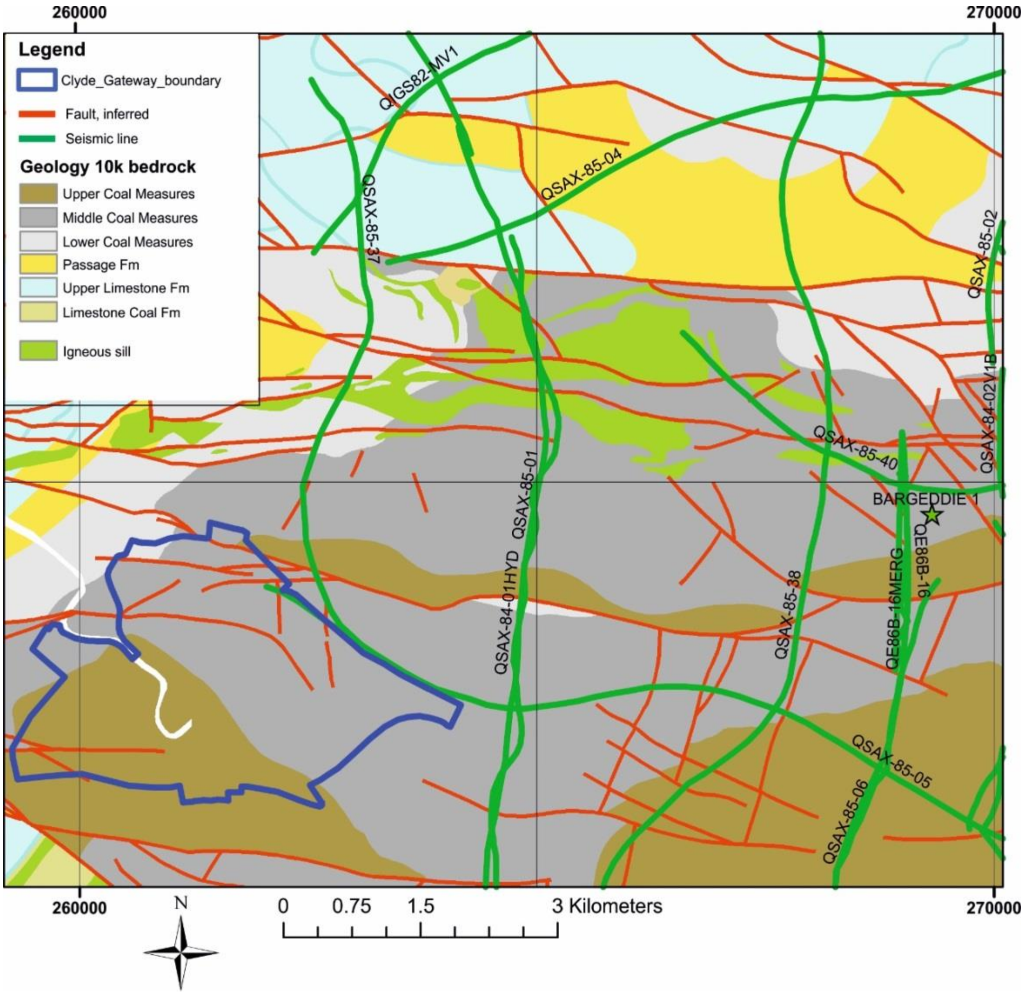


Figure 9 Location of Clyde Gateway area (blue outline), seismic lines (green) and Bargeddie 1 exploration well.

The Bargeddie 1 commercial hydrocarbon exploration well, drilled in 1989, is located 190 m south of seismic profile SAX-85-40 and provides information on the geological succession and velocity data that were used in the interpretation and depth conversion.

The DIGMapGB 1:50 000 and 1:10 000 bedrock and fault shapefiles were imported to Decision Space™ to guide and provide quality control on the subsurface interpretation.

A detailed Excel spreadsheet, containing time and depth information data from Bargeddie 1 exploration well was created.

2.2.4.3 INTERPRETATION METHODOLOGY

The seismic interpretation was carried out using Decision Space™ software. The seismic interpretation is based upon the Two-Way-Travel-Time (TWTT) to selected seismic events (Table 1) taken from the Bargeddie 1 commercial exploration well (Figure 10) and tied to the nearest (~190 m offset) seismic profile SAX-85-40 (Figure 11). Faults identified on the seismic data were verified on the 1:10 000-scale geological map and adjusted to fit where possible. The 1:10 000-scale map was also used to distinguish faults on the seismic data where initial interpretation had failed to identify them. The interpretation was guided by the 1:10 000-scale geological map showing formations mapped at outcrop as these are generally well-constrained by borehole data across the study area. The seismic events tied to the Bargeddie 1 well on seismic profile SAX-85-40 were then tied to key intersecting seismic profiles: SAX-85-38; SAX-85-05; SAX-85-37; IGS82-MV1 and SAX-85-01 that were closest to the Clyde Gateway area. An initial interpretation of seismic profiles adjacent to the Clyde Gateway area was imported to the existing 3D model which includes coal mine abandonment plan data for comparison.

Seismic TWTT event	TWTT in seconds from Bargeddie 1	Seismic Depth event	TVDSS in metres from Bargeddie 1
MFQ_ESIOS_TopPassageFm_v2	0.1478	MFQ_ESIOS_TPF_v2_DEPTH	211.20
MFQ_ESIOS_TopUpperLmstFm_v2	0.2122	MFQ_ESIOS_TULF_v2_DEPTH	303.20
MFQ_ESIOS_TopLmstCoalFm	0.4481	MFQ_ESIOS_TLCF_DEPTH	578.20
MFQ_ESIOS_TopLwrLmstFm	0.4662	MFQ_ESIOS_TLLF_DEPTH	606.40
MFQ_ESIOS_BaseLwrLmstFm	0.5194	MFQ_ESIOS_BLLF_DEPTH	698.20
MFQ_ESIOS_BaseResolvablePackage	n/a	MFQ_ESIOS_BRP_DEPTH	n/a

Table 1. Seismic events interpreted.

The Top Passage and Top Upper Limestone formations lie above the first sonic velocity recordings in the Bargeddie 1 well. TWTT ties were calculated from their recorded depths in the well using the equation ($y = 0.0007x$) derived from T/D relationship deeper in section and extrapolated back to zero intercept at Ground Level (GL) (Figure 12; and see Depth Conversion section below). These horizons occur at the base of a seismic package exhibiting relatively high amplitude and continuous seismic reflections representing the Scottish Coal Measures Group (Figure 11; Figure 12; Figure 15).

The Limestone Coal Formation has been significantly faulted out in the Bargeddie 1 well and the ***Base Upper Limestone Formation*** is also obscured by the fault plane (Figure 10). A seismic package above the ***Top Lower Limestone Formation*** was inferred to represent the ***Top Limestone Coal Formation*** seismic horizon. The seismic package tends to be more transparent, containing weaker and less continuous seismic amplitude reflections (Figure 11; Figure 12).

The Top Lower Limestone Formation seismic event was taken at a velocity increase, closest to its interpreted boundary in the Bargeddie 1 well (Figure 11; Figure 12).

The Base Lower Limestone Formation seismic event was taken at a velocity decrease, closest to the interpreted boundary in the Bargeddie 1 well. This event marks the top of the West Lothian Oil Shale (Figure 11; Figure 12).

The ***Base Resolvable Package***, the deepest seismic reflector picked, marks the perceived base of the seismic package that contains interpretable seismic events. This seismic package is interpreted to include the West Lothian Oil-Shale Formation. The seismic reflector picked does not represent a unique seismic event marked by a velocity/ density contrast between two different rock formations; it simply marks the base of a seismic package that contains a variety of different geological successions (Figure 12).

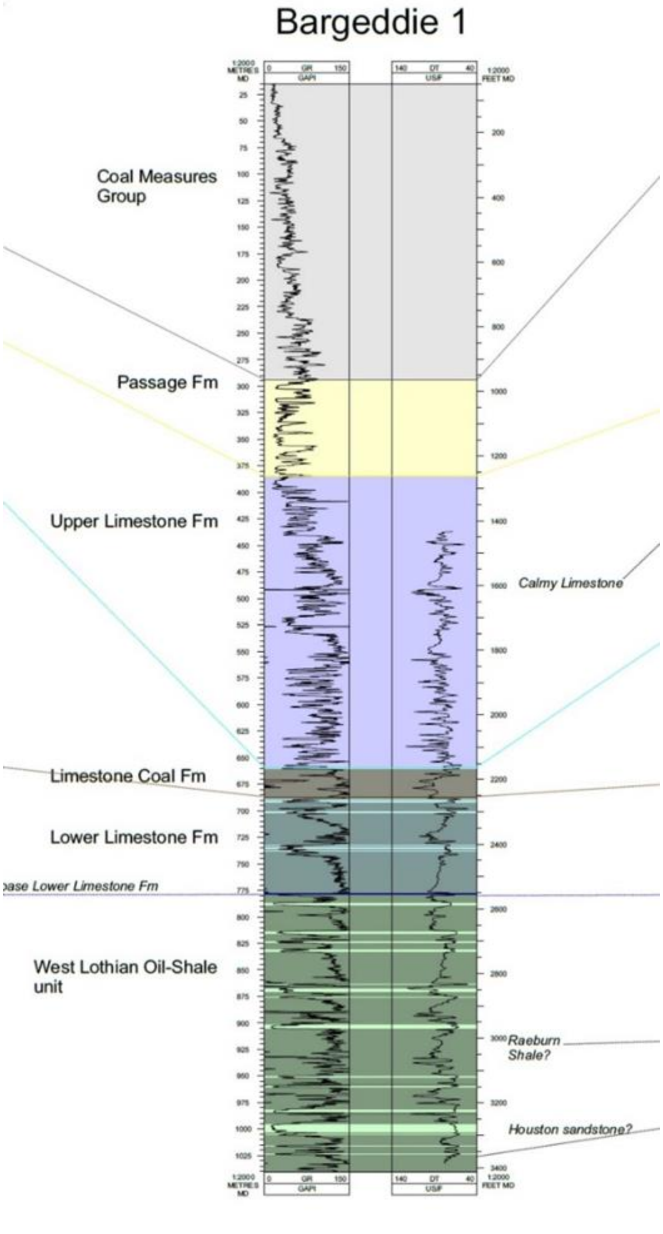


Figure 10 Bargeddie 1 well, reproduced from Monaghan (2014) ©DECC

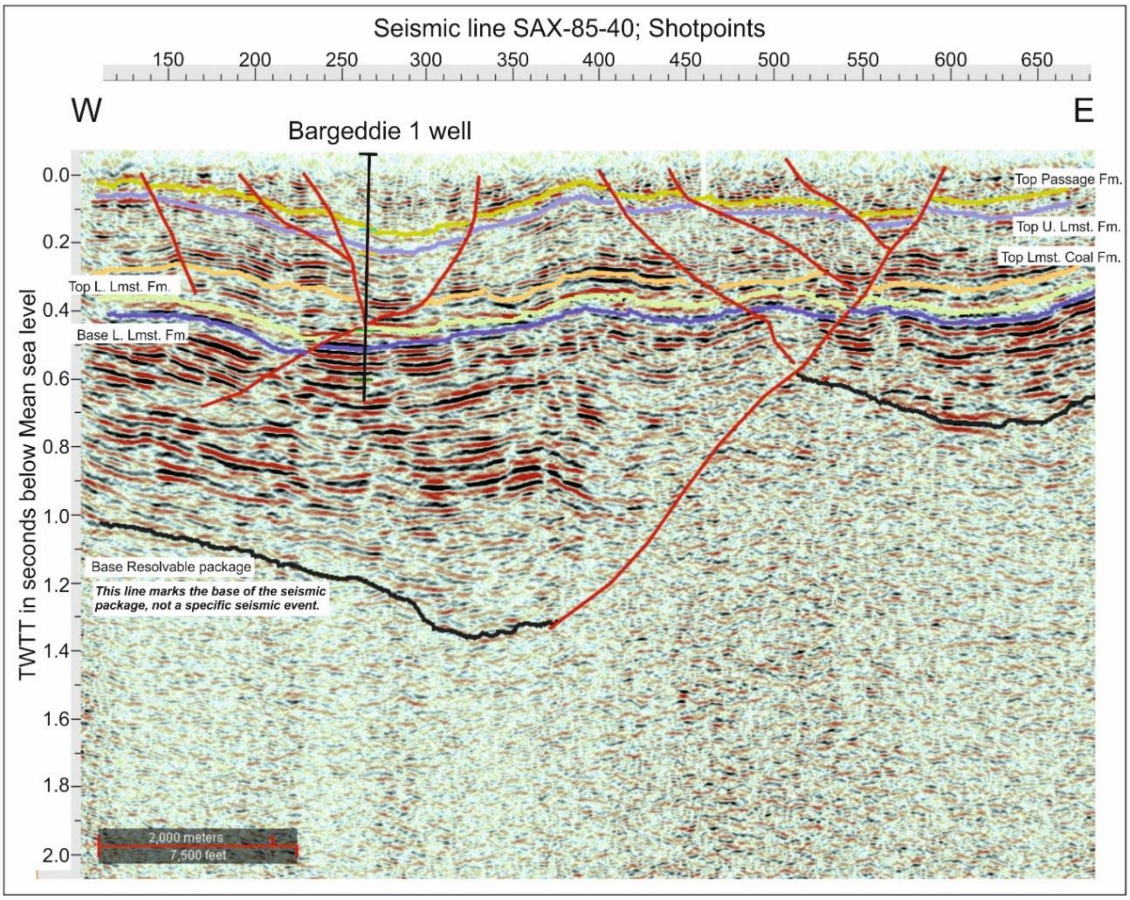


Figure 11 Detail from seismic profile SAX-85-40 showing location of Bargeddie 1 exploration well and interpreted seismic events. Seismic data reproduced with permission of UKOGL.

2.2.4.4 DEPTH CONVERSION

TWTT information from check shots and key formation boundaries were taken from the calibrated velocity and composite logs of the Bargeddie 1 well and plotted against True Vertical Depth SubSea (TVDSS) (Figure 12). There is a straight line relationship through all of the T/ D points; however, the extrapolation of this line to Ground Level does not intercept at zero. The equation for this line ($y=0.0006x+0.1128$) was initially used to depth convert the deeper seismic events in the Bargeddie 1 well (Figure 12).

In order to identify the TWTT of the Top Passage and Top Upper Limestone Formations in the Bargeddie 1 well it was necessary to convert their known TVDSS to TWTT as no time measurements were taken at this level in the Bargeddie 1 well. However, their tops lie at 211 and 303 m (TVDSS) respectively, and it was decided that the equation used for the deeper horizons and derived from a line (if extrapolated) that does not pass through the zero intercept would put these formation tops too deep in terms of TWTT. A different line was generated, specifying a zero intercept, and the equation for that line ($y = 0.0007x$) was applied to give the TWTT for the top Passage and Upper Limestone formations (Figure 12).

A quick comparison of depth converted values calculated from the Bargeddie 1 well data only with those derived using time/depth data from the a BGS well database, that covers the whole Midland Valley area, shows the latter to be around 30% deeper.

Further consideration of the time/depth relationship resulted in the application of a polynomial relationship, with an intercept of zero, to carry out a final depth conversion of the data; this curve provides an equation describing a time/depth relationship from zero intercept to 1200 m TVDSS. The equation for this line ($y = 795.5x^2 + 878.29x$) was used in a second depth conversion of all the seismic events in the Bargeddie 1 well where y = TVDSS (m) and x = TWTT (seconds) (Figure 13).

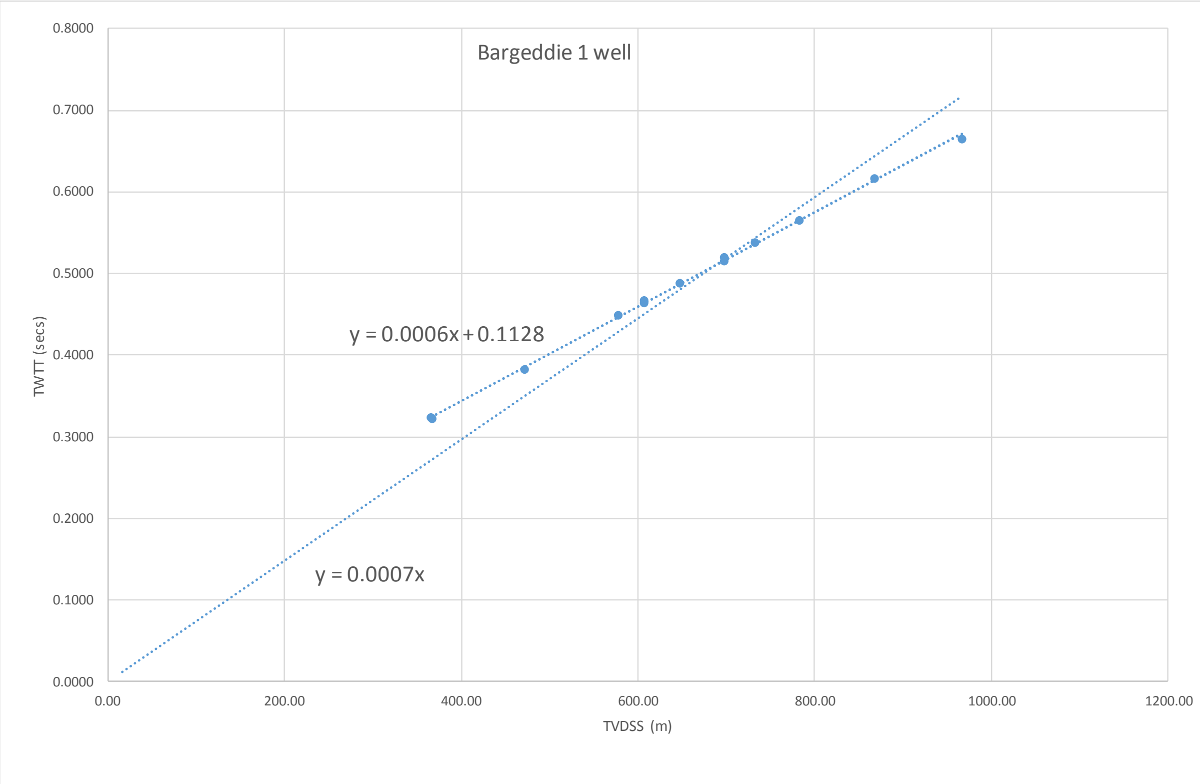


Figure 12 TWTT in seconds plotted against TVDSS in metres. The graph shows a straight line relationship between the Time/ Depth pairs measured in the well and described by Equation: *y = 0.0006x + 0.1128*. The graph also shows the straight line relationship but with Intercept = Zero, described by equation *y = 0.0007x*. This latter equation was used to calculate TWTT from TVDSS of the Top Passage and Top Upper Limestone formations.

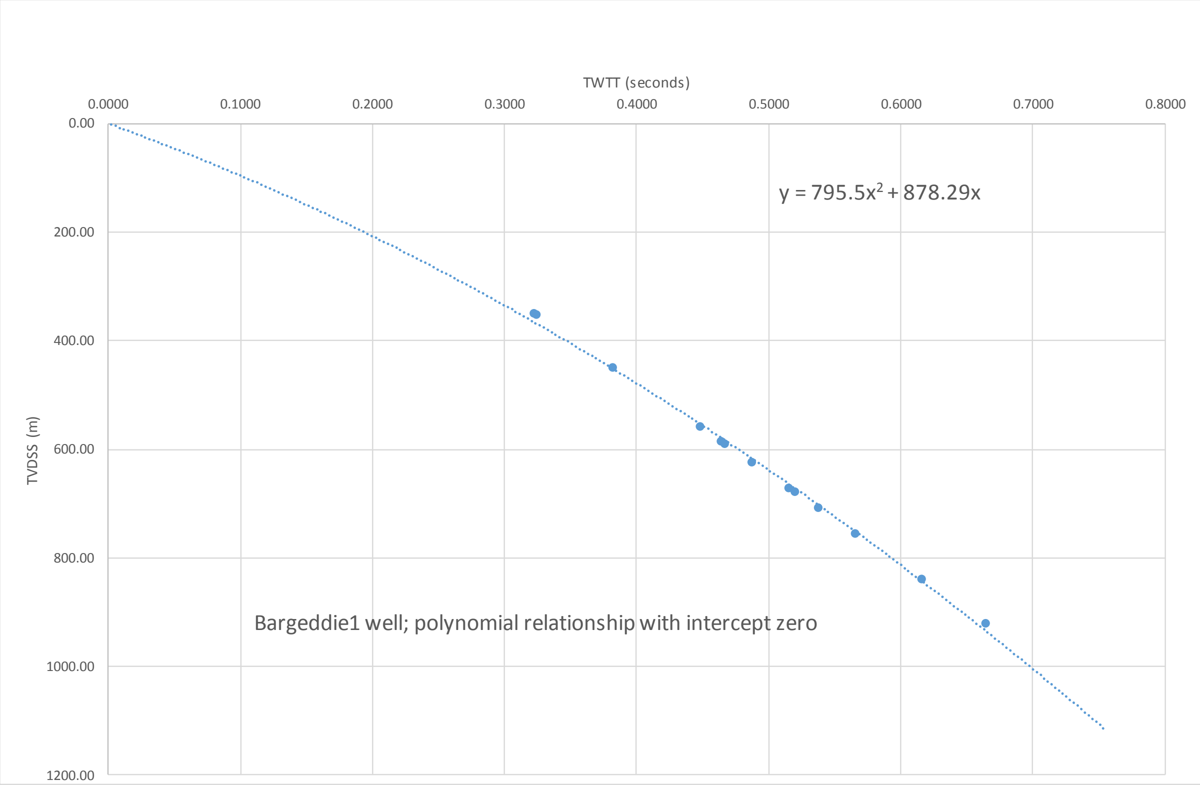


Figure 13 TWTT in seconds plotted against TVDSS in metres. The equation for this line was used in the final depth conversion.

2.2.4.5 Observations resulting from seismic interpretation

Structural/ stratigraphic - The seismic data used in this study were acquired in 1985 and show coherent reflections down to about 1.5 seconds TWTT. Displacements of seismic reflections can generally be tied to faults mapped on the 1:10 000-scale geological map. The map shows a series of dominantly east–west– to west-north-west–east-south-east—ESE–trending relatively continuous faults; these faults locally bound sets of shorter faults that have been mapped trending north-west to north-east.

Hooper (2003) describes a preferred tectonic model for the Carboniferous that begins with a predominantly transtensional dextral tectonic regime during the Namurian and Visean. Hooper (2003) suggests faults formed during this time would have oblique-slip (rather than normal) movements. Regional extension during the early Carboniferous resulted in the development of normal faults and reactivation of pre-existing (Caledonian orientated) faults. Regional shortening in the late Carboniferous resulted in the development of reversed faults (Hooper 2003). For this interpretation, the expected complicated nature of the subsurface, with potentially dip-slip, strike-slip, fault reversal and fault reactivation having occurred, has resulted in a variety of possible hanging-wall/ foot-wall stratigraphic relationships that the wide spacing and quality of the seismic data could not resolve. However, seismic interpretation of the seismic data does show evidence of post-depositional compression in the form of anticlinal features e.g SAX-85-40 (Figure 11), SAX-85-37 (Figure 14).

Seismic line SAX-85-37 (Figure 14) shows possible reverse displacement and compression on a southerly dipping fault at shotpoints 350 to 440 and its associated antithetic fault, resulting in the Upper Limestone Formation succession at outcrop juxtaposed with Coal

Measures. This is interpreted as being followed by reactivation of the fault in a normal or dip-slip displacement (Figure 14).

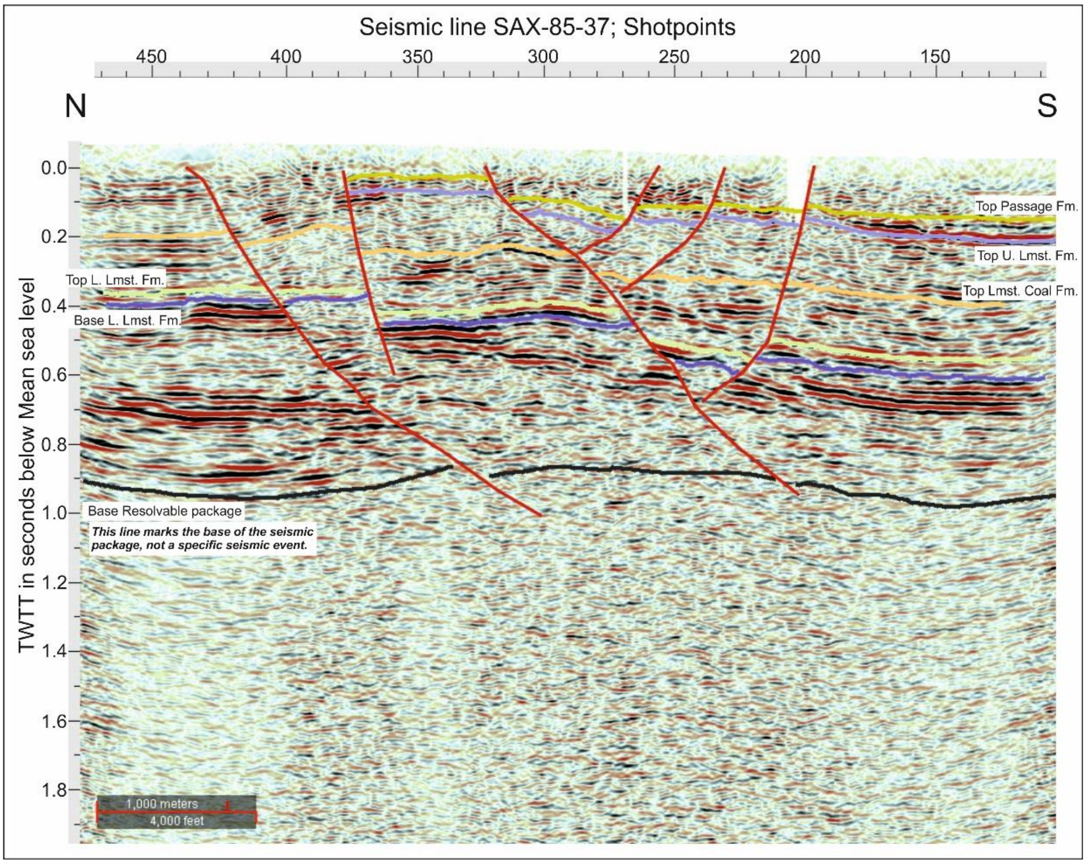


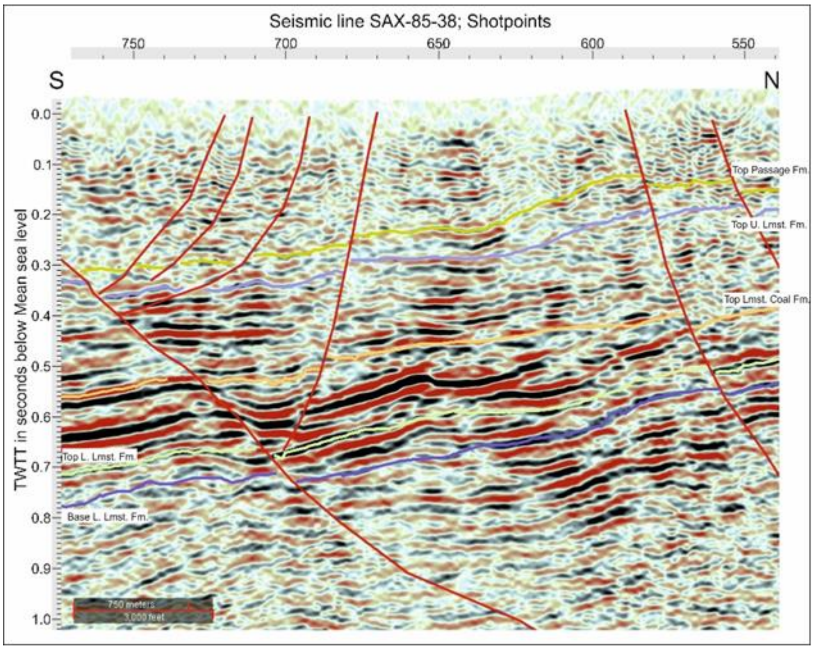
Figure 14 Seismic profile SAX-85-37 showing evidence for possible reverse movement on main faults. Seismic data reproduced with permission of UKOGL.

Seismic reflectors deepen gradually southwards. For instance, on seismic Line SAX-85-01, the Base Lower Limestone Formation is interpreted at around 400 msecs TWTT in the north deepening to nearly 800 msecs TWTT in the south. On seismic line SAX-85-37 the Top Lower Limestone Formation is interpreted at less than 400 msecs TWTT in the north deepening to 560 msecs TWTT southwards. In addition, possible onlap is observed within the West Lothian Oil-Shale Formation at shotpoints 310 to 250 (Figure 14).

Igneous features - Some seismic profiles show very high amplitude reflectors whose relationship with surrounding seismic events within the seismic package indicate they may be igneous sills; for instance, profile SAX-85-38 (Figure 15a) and SAX-85-01 (Figure 15b). Igneous sills have been mapped at outcrop in the study area and this interpretation of the seismic data indicates that sills could be expected to be present at different levels within the subsurface.

The Base Resolvable Package seismic reflector may, in places lie close to the top of the Clyde Plateau Volcanic Formation lavas, where these are expected to be present. On some seismic lines, continuous seismic reflectors occur beneath this seismic reflector, most noticeable on SAX-85-04 shotpoints 360 to 100 below 1 second TWTT) indicating a possible eastwards change in the succession at depth. However, sparsity of data meant this could not be followed on other lines.

Forsyth et al. (1996) describe a Penn et al. (1984) seismic interpretation of a c. 600 m thick Clyde Plateau Volcanic Formation on two IGS lines situated over 10 km to the north of Clyde Gateway, as well as a top Lower Devonian interpretation at c. 1 second.



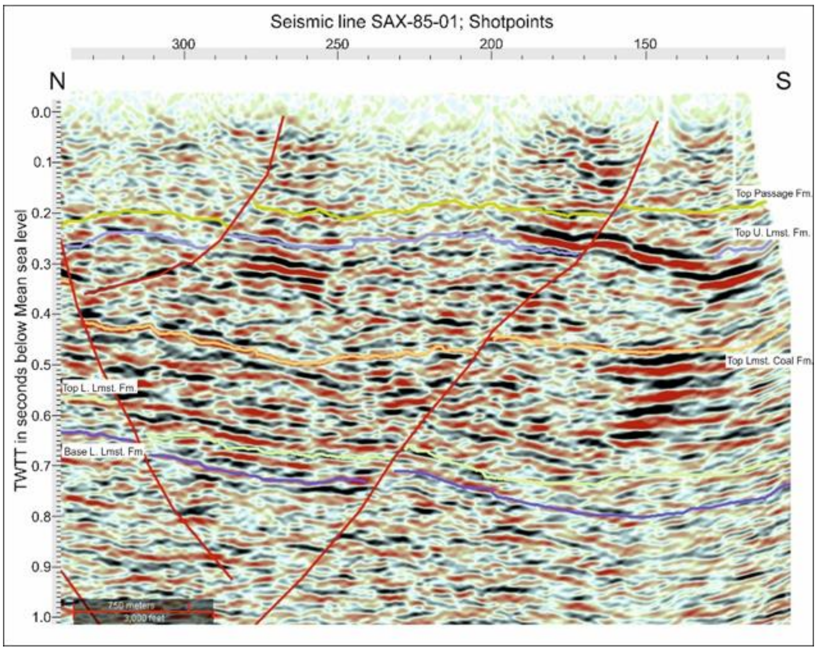


Figure 15 Above: Detail from seismic profile SAX-85-38, high amplitude events within the Limestone Coal and possibly lower part of Upper Limestone formations. These could be igneous sills (around 600 milliseconds, shotpoints 800 to 650). Below: Detail from seismic profile SAX-85-01, high amplitude events within and just below the Passage Formation could be igneous sills (around 250 milliseconds, shotpoints 107 to 196]. Seismic data reproduced with permission of UKOGL.

2.2.4.6 CONCLUSIONS

Interpretation of selected seismic profiles immediately adjacent to the Clyde Gateway area has confirmed the complex, faulted Carboniferous geology present. The seismic reflectors picked were identified and tied from the Bargeddie 1 exploration well that lies approximately 190 m from the nearest seismic profile. Confidence in the interpretation of the reflectors away from the well decreases as the stratigraphic relationships across faults are not always clear and are likely to be misleading due to the number of possible styles of fault movement that have occurred through time.

Another source of error is introduced in the depth conversion method utilised to allow inclusion into the 3D geological model. While the depth conversion may cause observed error when compared to surveyed-in mine plan data, and absolute depths may be wrong, structural and stratigraphic relationships should remain, provided there are no errors in the TWTT interpretation of seismic reflectors.

A better seismic interpretation of the subsurface would be facilitated by a denser grid of newer seismic lines. However, another cheaper option, if original field tapes are still available, would be to carry out re-processing of the original data. This proved to be successful for a similar vintage of legacy seismic data that imaged the Carboniferous strata in the Firth of Forth (Smith et al., 2011).

There is scope for the seismic interpretation to be improved using the existing dataset coupled with an iterative approach with the 3D model. The initial depth converted horizons, imported into the 3D model, were compared where possible with surfaces generated from mine working data. Potential next steps in the seismic interpretation would be to record the differences observed in the 3D model and then investigate possible reasons for these discrepancies. Closer examination of the events, particularly where they cross faulted boundaries, may reveal errors in the interpretation. In addition, the depth conversion method may also be a source of error that could be improved with selective inclusion of additional Time/ Depth information.

2.2.5 Map data

The Clyde Gateway area is located on the BGS 1:50 000-scale map sheets 30E Glasgow (1993 bedrock, 1994 superficial deposits) and 31W Airdrie (1992 bedrock, 1992 superficial deposits). BGS Memoirs form a definitive reference source for the geology of this area (Hall et al., 1998; Forsyth et al., 1996)

The central and eastern side of the study area is located on 1:10 000-scale map NS66SW that was revised in 2008. The western side is located on 1:10 000-scale map NS56SE. BGS hold some updated bedrock linework from around 2007 but this was not incorporated into a revised published map; the published version is from 1995.

Map data is available as GIS shapefiles (DigMapGB) or as scans (Mapviewer).

2.2.6 Gravity and magnetic data

BGS regional gravity and magnetic gridded datasets are based on data points between 1–2 km apart, there are only a handful of data points within the Clyde Gateway area and any interpretation at this scale is not appropriate. Over a larger area, Forsyth et al. (1996) suggest that sedimentary rocks may be underlain by the Clyde Plateau Volcanic Formation in the Airdrie (31W) map district. In the Glasgow map district (30E), Hall et al. (1998) describe gravity lows, and low frequency, low amplitude magnetic anomalies over Upper Palaeozoic sedimentary rocks (such as over the Clyde Gateway area). Areas with Clyde Plateau Volcanic

Formation at surface are characterised by gravity and magnetic highs that are interpreted to be caused by hundreds of metres of lavas and underlying basin intrusions (Hall et al., 1998).

No site specific or local surveys were located in the Clyde Gateway area using the BGS Geoscience Data Index (GDI).

2.2.7 Various bedrock property data

Data are lacking on bedrock properties at depths greater than a few tens of metres (see sections 4, 5, 7) but data exist from Carboniferous strata from deep boreholes and hydrocarbon exploration wells elsewhere across central Scotland.

Further data on rock properties at depths greater than a few hundred metres could be extracted from hydrocarbon exploration well records. Monaghan (2014, Appendix E) gives some XRD compositional data from deep core samples. Porosity, permeability rock strength and mineralogy data on from some deep core samples was measured by Heriot-Watt and BGS as part of the CASSEM CCS project in 2008/9 and is available from BGS NGDC. Whilst porosity of up to 17 % was measured in Upper Devonian-Lower Carboniferous sandstone core samples from depths up to 350 m, the highest permeability measured was 16 mD (where this unit is utilised as an aquifer near surface, much flow is via fractures). A mineralogical and petrological study of the same sandstone core samples highlighted porosity reduction by compaction processes, by authigenic chlorite and by a diagenetic ferroan dolomite and ankerite pore filling cement (Milodowski and Rushton, 2008); however dissolution of feldspar created secondary porosity.

2.3 3D DETERMINISTIC MODEL

Bedrock models were produced in GOCAD by interpolation of all available borehole, mine plan and map outcrop data in 2008 and 2011 (documented in Merritt et al., 2009; Monaghan et al., 2012). The bedrock model of the Clyde Gateway area was updated in 2016–17 to include any new borehole data and migrated to an improved workflow in GOCAD-SKUA 15.5 (Kearsey, 2017; Figures 16, 17, 18).

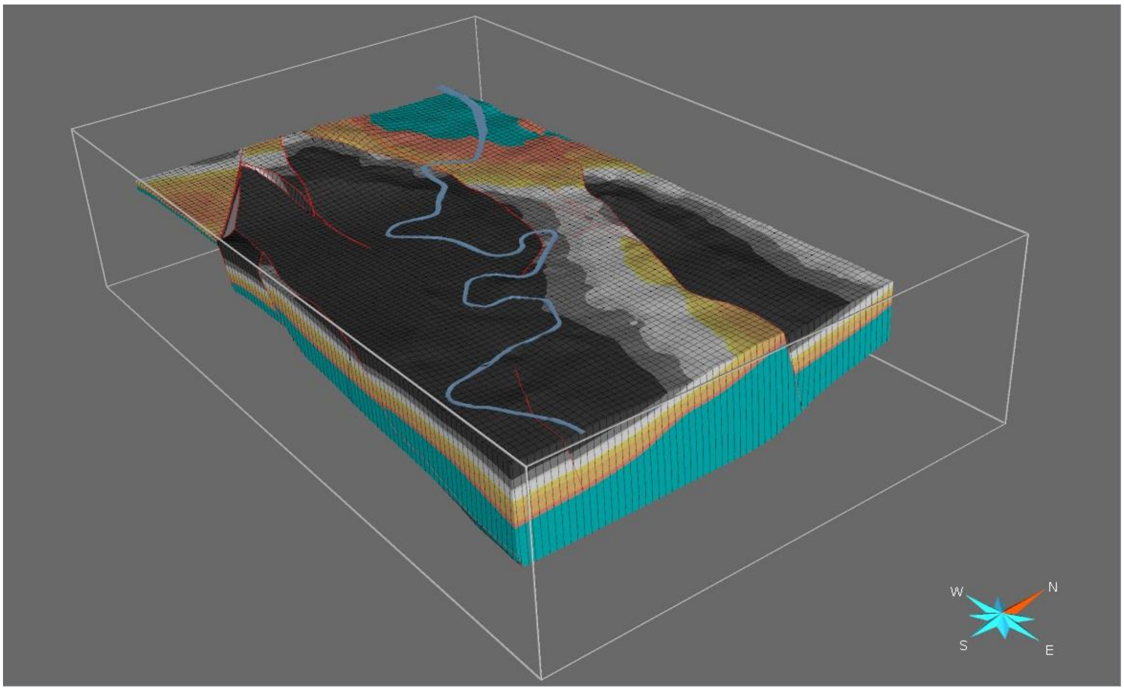


Figure 16 Overview image of the 7 by 4 km bedrock model to depths of -500 m. The Scottish Coal Measures Group is represented in the black to orange colours. The Passage, Upper Limestone and Limestone Coal formations are in blue.

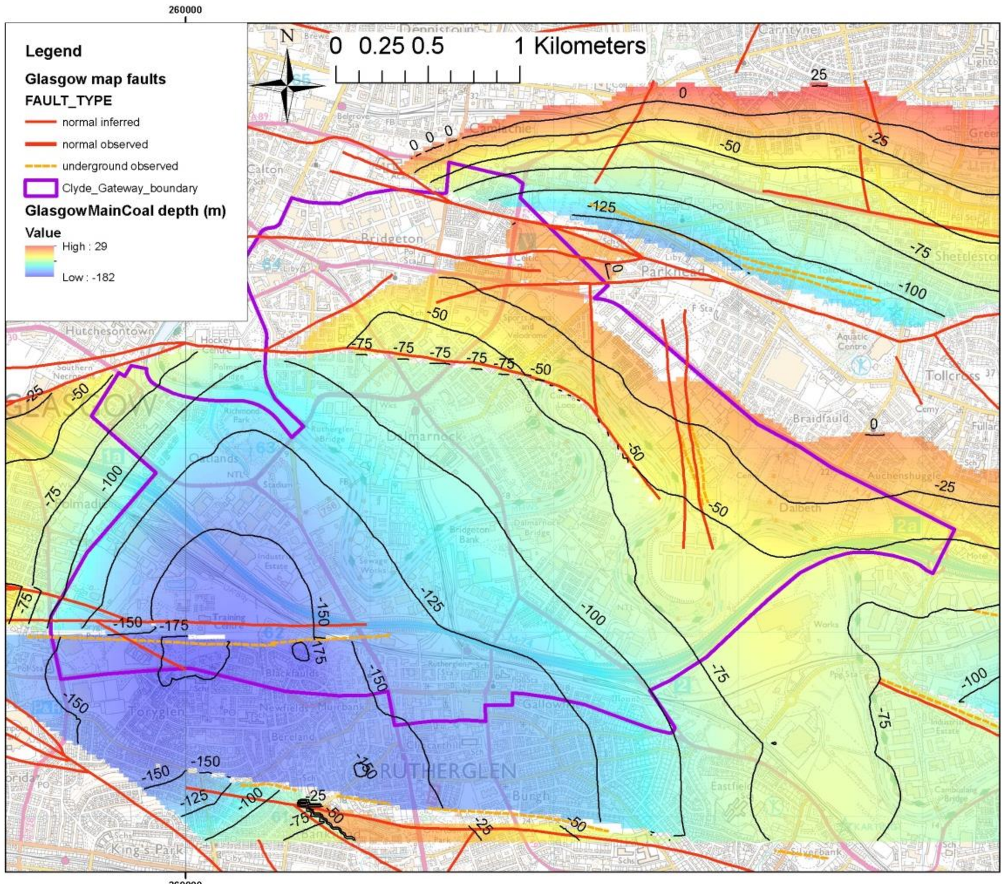


Figure 17 Depth grid to the Glasgow Main Coal from the bedrock model described in Kearsey (2017). Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2017. Licence number 100021290 EUL

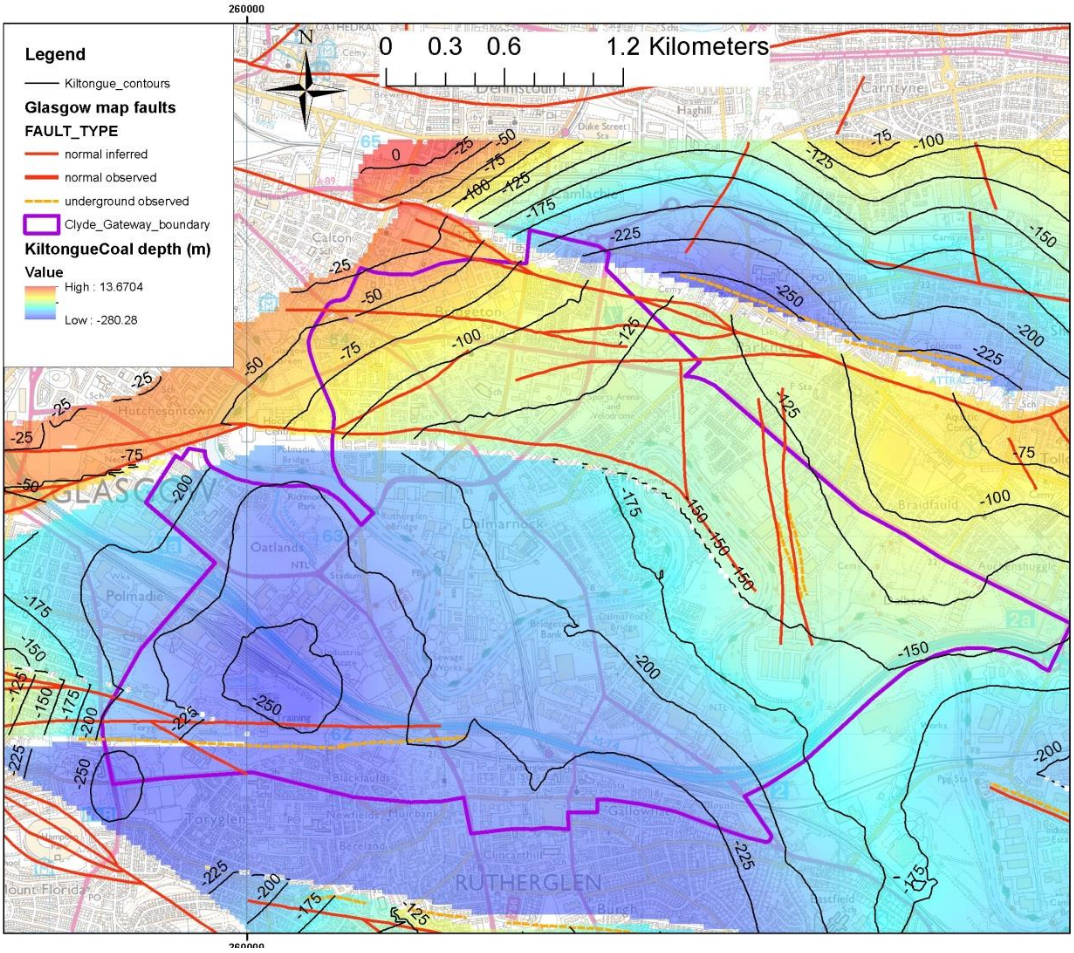


Figure 18 Depth grid to the Kiltongue Coal from the bedrock model described in Kearsey (2017). Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2017. Licence number 100021290 EUL

2.3.1 Model revision

The bedrock model was revised to include a limited amount of new borehole information and to utilise up-to-date 3D modelling software (Kearsey, 2017). The result is a consistent faulted geological model including in areas poorly constrained by data. A limitation of the model is that it is a best fit of highly variable borehole and mining data, rather than an exact fit of data points.

Seismic data are not currently used in the 3D bedrock model because whilst largely in agreement with borehole and mine data, there are inconsistencies in either seismic interpretation or depth conversion. These result in a mismatch between the borehole/mine and depth-converted seismic interpretation picks which could be resolved in an iterative interpretation and modelling process. However, since only a limited section of a seismic line is within the smaller area modelled in detail, and it is to the north-east of the main area of interest, this iterative interpretation and modelling step was not deemed to be a top priority at the current time.

2.4 BEDROCK DESCRIPTIONS, CONCEPTUAL MODELS AND UNCERTAINTIES

The deepest borehole drilled from surface within the Clyde Gateway area is the Dalmarnock borehole/shaft [NS66SW BJ236] to a drilled depth of 294 m. This is interpreted to penetrate beyond the base of the Scottish Lower Coal Measures Formation and into the top of the Passage Formation (Figure 19). A 173 m long underground borehole drilled from the pavement of the mined Kiltongue Coal in the Govan no 5 pit [NS66SW BJ197] is interpreted to prove the base of the Scottish Lower Coal Measures, the Passage Formation and the top part of the Upper Limestone Formation and documents the bedrock geology for the area to around 430 m.

Whilst the information is very sparse, the records that exist indicate the 'expected' Carboniferous sequence.

The Bargeddie 1 hydrocarbon exploration well, situated 5.5 km to the east of the study area, records over 1000 m of the Carboniferous succession, terminating in the West Lothian Oil-Shale Formation (Figure 19). There are also a small number of boreholes to the east and north of the Clyde Gateway study area that penetrate as deep as the Index Limestone (base Upper Limestone Formation).

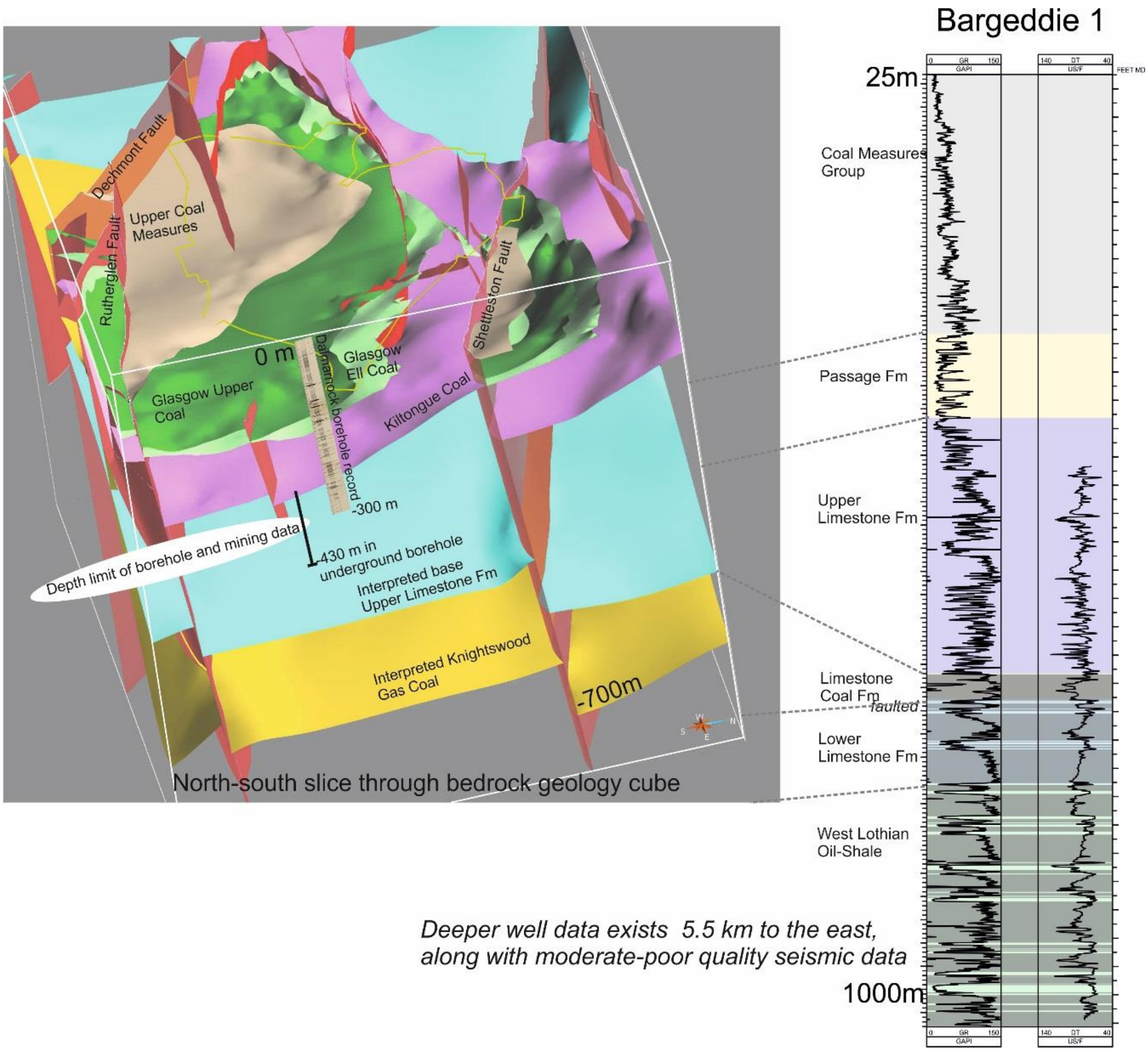


Figure 19 Illustration of the depth limit of borehole data within the Clyde Gateway area in the 2011 bedrock geology model, and the single hydrocarbon well available to the east. Interpretation of Bargeddie 1 from Monaghan, 2014.

The bedrock geology at depths greater than 430 m in the Clyde Gateway area is therefore interpreted from adjacent areas where strata beneath the Coal Measures are present at shallower levels, and are extensively penetrated by boreholes, plus occasional rock outcrops. The Carboniferous succession is proved to be of variable thickness (Table 2) and borehole prognosis requires detailed work on local thickness variations and trends.

Unit	Bargeddie 1 well	Boreholes in area	NE56SE 10k sheet GVS	NE66SW 10k sheet GVS	Glasgow 50k GVS	Glasgow Memoir	Airdrie 50k GVS	Airdrie Memoir	*Cumulative minimum thickness (to base)*	*Cumulative maximum thickness (to base)*
Upper Coal Measures	275 (Coal Measures Group)	230+ Coal Measures Group	88+	86+	100	100	264	270	*100*	*270*
Middle Coal Measures			150	157	162	100	192	195	*200*	*465*
Upper Coal Measures			110	96	105	100	129	135	*300*	*600*
Passage Fm	90	84 m NS66SW197	44	81	78	80	189	215	*378*	*815*
Upper Limestone Fm	275	55+ NS56SE227	234	33+	270	270	294	270	*648*	*1085*
Limestone Coal Fm	21.5 (faulted)	180+ NS56SE255	409		312	300	345	350	*948*	*1494*
Lower Limestone Fm	95	172 NS56SE255	183		108	80	180	180	*1028*	*1677*
Lawmuir, West Lothian Oil-Shale Fm	265.5+ (WLOS)				189	0-330	192	195	*1028*	*1943*
Kirkwood Fm					141	0-70	66	65	*1028*	*2084*
Clyde Plateau Volc. Fm					450	450	804	c. 700	*1478*	*2888*
Clyde Sandstone Fm					72	0-80	90	0-110	*1478*	*2998*
Ballagan Fm					102	0-180	204	0-380	*1478*	*3378*
Kinnesswood Fm					171	180	135	140	*1618*	*3558*
Stratheden Group/ Stockiemuir Sandstone Fm					402	400		35+	*1653*	*3960*
Strathmore Group /Teith Sandstone Fm					201	200+			*1853*	*4161*

Table 2 Thickness estimates (metres) and variability to inform deep borehole prognosis end members. The study area is located in the southern corner of the Airdrie and Glasgow 1:50 000-scale geological maps. The yellow highlighted cells represent the estimated maxima and minima for a 2 km deep borehole which could reach volcaniclastic deposits above the Clyde Plateau Volcanic Fm., or the Lower Devonian in a more condensed succession.

2.4.1 Unit descriptions

This section provides a summary of each stratigraphic unit to inform borehole planning.

2.4.1.1 Scottish Coal Measures Group

The Scottish Coal Measures Group is characterised by coal-bearing fluvio-deltaic sedimentary rocks in cyclical sequences of mudstone, siltstone, seatearth (rootlet-bearing palaeosol), sandstone and coal. The depositional environment was interpreted to be a broad flat, coastal deltaic plain in which coal swamp conditions occurred frequently. The Group is divided into three formations, based on lithological variations, marine band biostratigraphy and non-marine macrofossil and palynological assemblages.

1. The Prospecthill borehole [NS56SE BJ393] is representative of the **Scottish Upper Coal Measures Formation** (UCMS, Bolsovian, Westphalian C, up to c.80 m thick) succession, containing a 3m mudstone that includes the Aegiranum Marine Band, the 60 m thick Westmuir Sandstone, and 23 m of argillaceous rocks including a thin coal and the Bothwell Bridge Marine Band (Hall et al., 1998). Red-purple staining is characteristic of the formation, though some beds retain their original pale grey colour. The formation is not known to contain any mined coals within the Clyde Gateway area.
2. The **Scottish Middle Coal Measures Formation** (MCMS, Duckmantian, Westphalian B) is described by Hall et al. (1998) as being 160 m thick (thinner than in most parts of the Scottish coalfields), and to contain an unusually high proportion of mudstone and siltstone with rare fluvial sandstones. This unit contains the thickest mined coals such as the Glasgow Upper, Glasgow Ell, Glasgow Main, Splint and Virgin (Figure 20). Further details of the succession are given in Hall et al. (1998), Hinxman et al. (1920), and Clough et al. (1926).

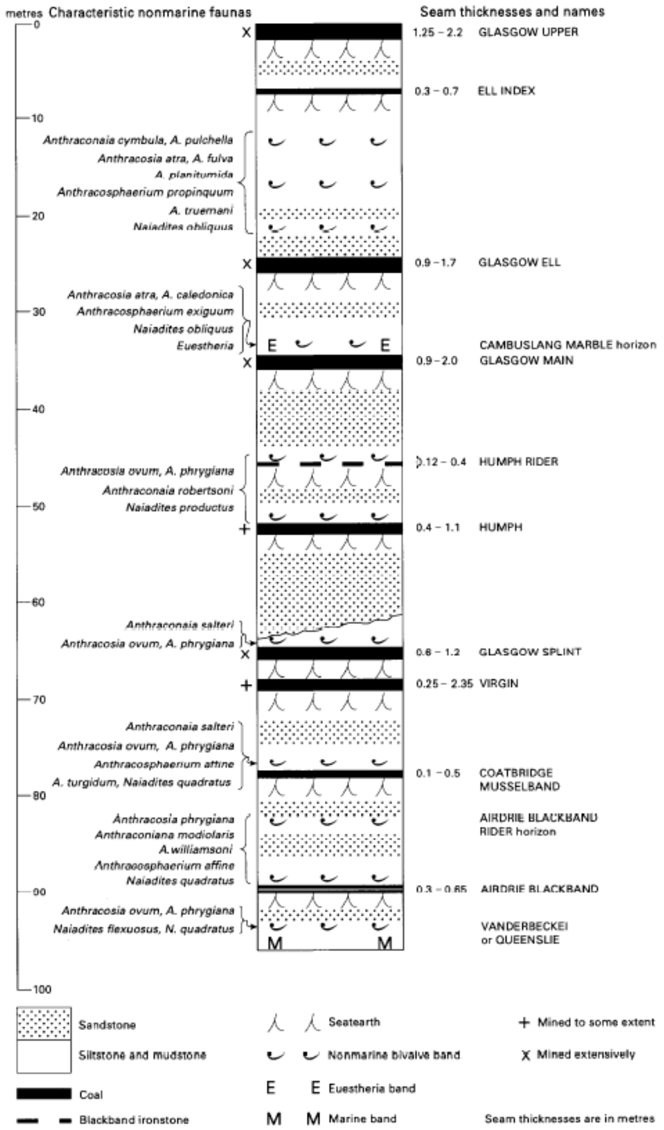


Figure 20 Vertical section of the Scottish Middle Coal Measures Formation from Hall et al. (1998).

3. The **Scottish Lower Coal Measures Formation** (LCMS, Langsettian, Westphalian A, *c.*100 m thick) consists of a basal sandstone-seatearth sequence, a middle part with coals up to 0.75 m thick and an upper sandstone-seatearth dominated sequence with several coals (Hall et al., 1998). The Kiltongue and Airdrie Virtuewell coals were mined from Govan no 5 pit (in the south-west of the Clyde Gateway area).

2.4.1.2 Passage Formation

The Passage Formation (PGP, Namurian-Westphalian A) is thinner in the Clyde Gateway area than in other parts of central Scotland, reaching around 85 m in an underground borehole [NS66SW BJ197] in Govan no. 5 pit. It is dominated by sandstone, some coarse-grained, with red-purple-green-yellow mudstone, seatclay and fireclay. Records of bedded mudstone, coal and marine bands are rare; however the No 3 Marine Band is interpreted in the Alexandra Parade borehole [NS66NW BJ408] (Forsyth et al., 1996) to the north of the Clyde Gateway area. The Passage Formation is interpreted as a dominantly fluvial system with many minor unconformities (Hall et al., 1998).

The Passage Formation represents a target geothermal aquifer for this study.

2.4.1.3 Upper Limestone Formation

The Namurian (Pendleian-Arnsbergian) Upper Limestone Formation (ULGS) is proved in boreholes outside the Clyde Gateway area and interpreted in the base of the Govan no. 5 pit underground borehole [NS66SW BJ197]. It reaches around 270 m in thickness. The unit is characterised by cyclical sequences of mudstone, siltstone, seatrock, coal, sandstone and limestone. In places, cyclic sequences are replaced by thick, medium- to coarse-grained sandstones with markedly erosive bases; for example, the Upper Drumbreck and Cadgers Loan sandstones north of the River Clyde, and the Barrhead Grit up to 55 m thick in south-west Glasgow (Hall et al., 1998). Depositional environments are interpreted as ranginf from shallow seas, to deltaic and alluvial plains and river channels (Hall et al., 1998).

2.4.1.4 Limestone Coal Formation

Proved in boreholes outside the Clyde Gateway area, the Limestone Coal Formation (LSC, Namurian, Pendleian) comprises cycles of coal, mudstone, siltstone, sandstone, seatearth and coal with some thicker mudstone intervals (e.g. Black Metals Marine Band), ironstone and limestone. Thickness across the wider Glasgow area varies from 270 to 350 m (Hall et al., 1998). The numerous coals range from 0–1.8 m in thickness and have been mined extensively in areas from the west to north-east of the Clyde Gateway area. The majority of sandstones within the succession are fine grained. Rarely, medium- and coarse-grained channel fill sandstones with erosive bases which cut out coals, are up to around 20 m thick (e.g. Nitshill Sandstone, Cowlairs Sandstone; Hall et al., 1998).

2.4.1.5 Lower Limestone Formation

In the wider Glasgow area, the Lower Limestone Formation (LLGS, Brigantian) thickens eastwards from 110 m to around 180 m. The unit is dominated by bedded mudstone with siltstone, sandstone, limestone and thin coal and ironstone. The depositional environment is interpreted as a quiet marine and non-marine backwater with sandy lobes extending from the east (Hall et al., 1998).

2.4.1.6 Strathclyde Group

In areas west and north-west of the Clyde Gateway area, the Visean age Strathclyde Group comprises sandstone, mudstone, thin coal, seatearth and conglomerate of the Lawmuir Formation (LWM) and the underlying volcanic detritus of the Kirkwood Formation (KRW; Hall et al., 1998). The unit ranges from thicknesses of 10’s to 200 m and is interpreted as having been deposited in fluvial and other environments with a series of marine incursions. East of the Clyde Gateway area, similar Brigantian age strata proved below 780 m in the Bargeddie 1 hydrocarbon exploration well are assigned to the West Lothian Oil-Shale Formation (WOLS), as a basinal equivalent of the Lawmuir Formation (Monaghan, 2014). Lack of data creates uncertainty in the character of Visean sedimentation underlying the Clyde Gateway area (see section 2.4.3 below).

2.4.1.7 Clyde Plateau Volcanic Formation

A succession of up to 1000 m of basaltic to trachytic lavas and volcaniclastic deposits constitutes the Clyde Plateau Volcanic Formation. This forms the Campsie, Kilpatrick, Renfrewshire and Beith-Barrhead hills surrounding Glasgow. Based on seismic reflection data from c.6 km to the north of the Clyde Gateway area, the lavas are inferred to extend southwards from the Campsie Fells, beneath the upper Carboniferous sedimentary basin. The formation is present at outcrop some 2 km to the south of the Clyde Gateway area, in the footwall block of the major Dechmont Fault structure. However, the extent of these volcanic rocks beneath the upper Carboniferous sedimentary basin in the vicinity of the Clyde Gateway area is unknown. This is an important potential constraint, and significant uncertainty, for any deep drilling in the Clyde Gteway area

2.4.1.8 Inverclyde Group

The character of the Inverclyde Group is inferred from outcrops beneath the Clyde Plateau Volcanic Formation, some distance north of the Clyde Gateway area. The fluvial Clyde Sandstone Formation (CYD, up to 80 m, Tournaisian-Visean) is underlain by interbedded mudstone and dolomitic limestone of the marginal marine-lagoonal Ballagan Formation (BGN, up to 180 m, Tournaisian) and sandstone and concretionary carbonates of the fluvial Kinnesswood Formation (KNW, up to 250 m, Tournaisian).

2.4.1.9 Stratheden Group

Upper Devonian sandstones are exposed beneath the Inverclyde Group to the north of the Campsie and Kilpatrick Hills and west of the Renfrewshire Hills, at significant distances (25-40 km) from the Clyde Gateway area. The >400 m Stockiemuir Sandstone Formation comprises largely fluvial and aeolian sandstone, is a partial lateral equivalent of the Knox Pulpit Formation of Fife and, along with the Kinnesswood Formation is considered as a potential hot sedimentary aquifer geothermal resource (Hall et al., 1998, Browne et al., 1985). The presence, depth, thickness and character of such a unit beneath the Clyde Gateway area is very uncertain.

2.4.1.10 Igneous intrusions

Olivine dolerite sills are proved at various levels within Carboniferous sedimentary strata in the vicinity of the study area:

- Within the basal Passage Formation to upper Upper Limestone Formation and within upper parts of the Limestone Coal Formation on NS56SE (BGS 1995), proved outwith the Clyde Gateway area
- Within lower parts of the Middle Coal Measures and upper parts of the Lower Coal Measures on the generalised vertical section of NS66SW (BGS 2008) but not present at surface on the map sheet (mapped at surface in the sheet to the north). A relatively small number of boreholes record igneous intrusions to the north of the Clyde Gateway area e.g. four intervals of dolerite from 4–22 m in thickness in the Crown Brewery borehole [NS66SW BJ 34], at Camlachie.

No dykes are recorded on the BGS 1:10 000-scale map of the Clyde Gateway area, or in mine plan data, though these are common in some other parts of central Scotland. A systematic examination for records of igneous rocks within the existing borehole record dataset should be undertaken once potential drilling sites are identified.

2.4.2 Sand body geometry

The likely volume of sand bodies within the heterolithic Carboniferous succession of central Scotland is one factor in the sustainability of a hot sedimentary aquifer geothermal resource. The sandstones are interpreted to have been deposited in a variety of environments from marine, deltaic to fluvial and aeolian (e.g. Hall et al., 1998; Browne et al., 1999; Read 1988a, 1989). Sandstone beds/units range in thickness from millimetres to tens of metres within a mixed lithology succession and, where the thickest sandstone units are exposed or correlated in boreholes, commonly have localised spatial extents interpreted as fluvial or fluvio-deltaic channel systems (e.g. Hall et al., 1998). The exception in the upper Carboniferous sequence is the sandstone-dominated Passage Formation that is interpreted as a dominantly fluvial succession containing many minor unconformities (Hall et al., 1998; Read 1988b).

Examples of sandstone bodies in the vicinity of the Clyde Gateway area are summarised in Table 3 below and in Figures 21, 22.

Stratigraphic Unit	**Summary of known thickness/ extent of sand body in Glasgow area**
Passage Formation	Govan no 5 pit shaft proves mainly sandstone (84 m thick), interpreted as fluvial with minor unconformities (Hall et al., 1998).
Upper Limestone Formation	Barrhead Grit (55 m, in west of Glasgow), Giffnock sandstone, Cadgers Loan Sandstone
Limestone Coal Formation	Nitshill Sandstone, Cowlairs Sandstone (beneath the Index Limestone). Maximum 20–25 m
Lower Limestone Formation	Various levels but laterally discontinuous
Lawmuir Formation	Hall et al. (1998) document some thick sandstones to the west of the study area, laterally variable
West Lothian Oil-Shale Formation and equivalents	Sandstones were conventional hydrocarbon targets across Central Scotland e.g. Bargeddie 1, Salsburgh etc

Table 3 Summary of main sandstone units documented beneath the Coal Measures Group in the vicinity of the Clyde Gateway area

Figure 21 Passage Formation sandstone, Levenseat silica sand quarry, Fauldhouse, West Lothian P708158 BGS©NERC.

Figure 22 Example of variable sand body geometry (centre) within Limestone Coal Formation strata, Blindwells Opencast Coal Site, East Lothian, P219897 BGS©NERC

Further research on the geometry of sand bodies within the Passage and Upper Limestone Formation, linked to their physical properties and measured flow yields would be beneficial for improved understanding of potential hot sedimentary aquifer geothermal targets likely to be encountered in the Clyde Gateway area. This could involve combining the legacy borehole and well dataset, previous work, outcrop exposures with the significant worldwide knowledge of fluvial hydrocarbon reservoirs and reservoir properties.

2.4.3 Conceptual understanding of geology at depth

As has been highlighted above, uncertainty on the likely lithological variations at depth within the subsurface beneath the Clyde Gateway area can be reduced by using regional data and knowledge. Palaeogeographic reconstructions of the depositional environment through time form an effective tool in synthesis of the complex tectono-stratigraphic setting that is interpreted for the Carboniferous of central Scotland.

As well as the overarching regional picture described in overview publications and BGS memoirs (Forsyth et al., 1996; Hall et al., 1998; Browne et al., 1999; Read et al., 2002), key papers documenting palaeogeographic reconstructions include:

Scottish Coal Measures Group: Read (1989) shows a uniform Westphalian A succession to the south-east of Glasgow

Passage Formation: Read (1988b) shows coarse clastic input towards Glasgow and a basal disconformity towards the Dechmont Fault

Upper Limestone, Limestone Coal, Lower Limestone formations: Goodlet (1957) showed a shale-dominated lithofacies map of the Lower Limestone Formation in the vicinity of Glasgow. Wilson (1989) used macrofossil assemblages to deduce the depositional environments of limestone beds and highlighted an eastern origin for marine transgressions. In the Limestone Coal and Upper Limestone formations, Read (1988) highlights coarse clastic input from the east-north-east towards the south of Glasgow. The response of the channel systems to sea level variations is illustrated in Read (1994) in which there is a continued channel system towards the Clyde Gateway area, but which at relative high sea level is shown as submerged beneath brackish water. Using deep hydrocarbon wells and boreholes, Monaghan (2014) highlights a high percentage of shale (mudstone/siltstone) within the succession in the Glasgow area. Hooper (2003) provides details of sedimentology and notes the lack of basin marginal alluvial fans.

West Lothian Oil-Shale Formation and lateral equivalents of the Strathclyde Group: Loftus and Greensmith (1988) highlighted the facies variability of an oil-shale lake, volcanism, fluvio-deltaic and marine sedimentation. Monaghan (2014; Figure 23) produced additional time slices and highlighted the westward extension of the West Lothian Oil-Shale Formation towards the Glasgow area, as proved in the Bargeddie 1 well drilled in 1989.

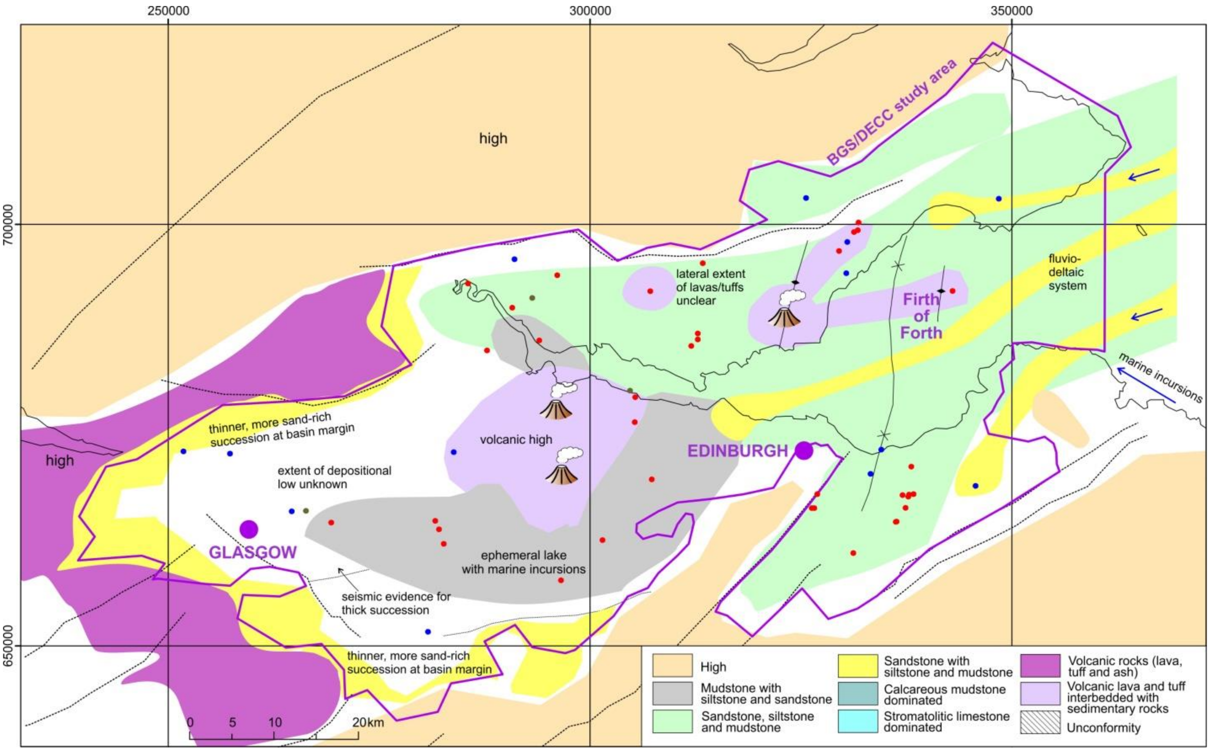


Figure 23 Regional paleogeographical reconstruction, Latest West Lothian Oil-Shale Formation times (near the top of the unit, c.331 Ma, NM palynomorph zone). Evidence is patchy and the reconstruction is tentative. Dashed lines are faults and folds with evidence for active growth from Monaghan 2014©DECC.

Further work on semi-regional palaeogeographic reconstructions using data from in and around the Glasgow area would be highly beneficial to better understand predicted lithological variability at depth in the Clyde Gateway area, as a tool to inform pre-drill borehole prognosis.

Common to the majority of published work are the long-lived high areas underlain by the Clyde Plateau Volcanic Formation, that form an enclosed western end of Carboniferous sedimentary basins. An initial conceptual understanding of the generalised setting (Figure 24) highlights possible end members of deposition adjacent to the Dechmont Fault structure and within the upper Carboniferous basin, bounded by the volcanic uplands of the Beith-Barrhead hills to the south and the Campsie Fells at some distance to the north.

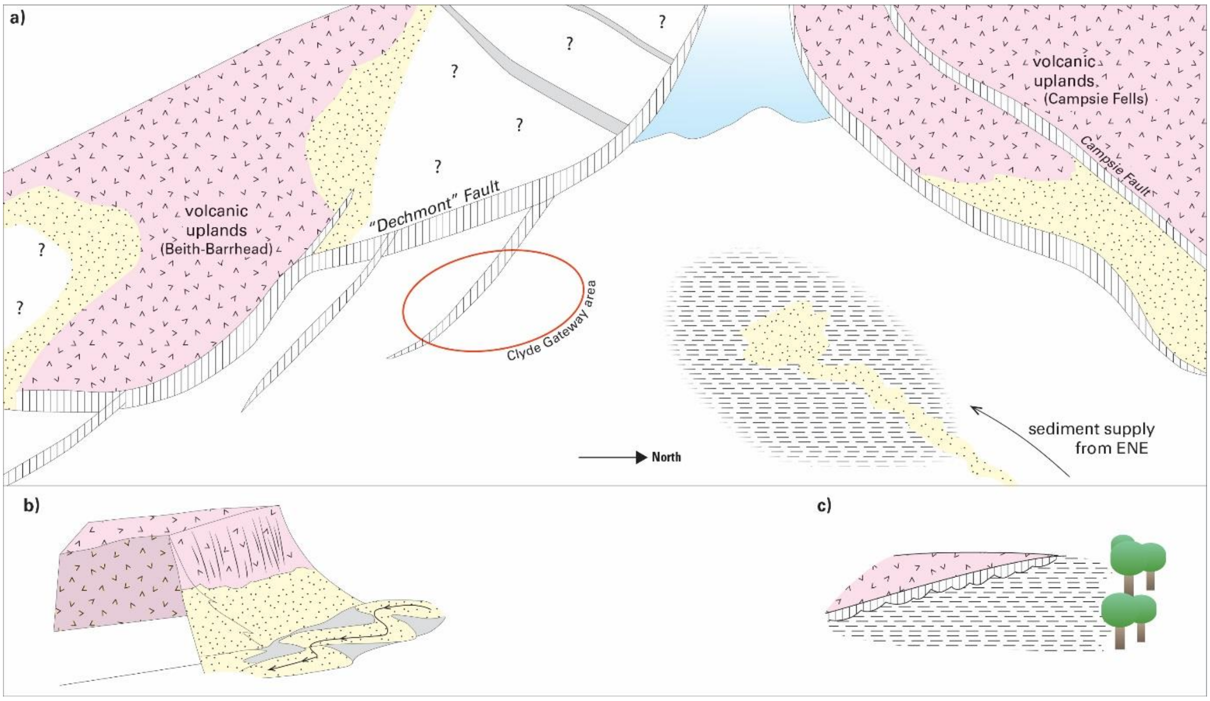


Figure 24 Initial 3D conceptual ideas on palaeogeography in the Clackmannan Group (e.g. Lower Limestone Formation) with a bearing on location and thickness of sandstones. a) an interpretation of palaeogeography with fault planes highly exaggerated b) potential fluvial end member of deposition, though note this kind of fault-controlled sedimentation is rarely evidenced in the Carboniferous of central Scotland c) potential lacustrine/brackish siltstone/mudstone-dominated end member with little fault relief.

Further development of the geological platform should focus on documenting and reducing uncertainty in the deep bedrock geology of the Clyde Gateway area.

2.5 FAULT DAMAGE ZONES

Faults can behave as pathways or baffles to fluid (or both simultaneously) and can have a significant impact on subsurface temperatures due to their influence on rock permeability and resulting impacts on fluid flow pathways and heat transport. Fault damage zones in brittle rocks tend to fracture, creating breccia or joints (Bense et al., 2013). Often, the damage zone around the fault core can be much more extensive and hydraulically more important, contributing more towards bulk permeability than the fault core (10’s to 1000’s of meters in thickness perpendicular to the fault strike compared with 0.1 to 10 m thickness).
Hydrogeological and geothermal considerations relating to faults and fracture zones are given in section 5.5 below, this section presents preliminary analysis of possible fault damage zone widths based on faults included in the approved version of the bedrock model (Monaghan et al., 2013) that covers the Clyde Gateway area.

2.5.1 Background

There is generally a broad positive relationship between fault zone width and fault throw (e.g. Beach, 1999; Fossen and Hesthammer, 2000; Savage and Brodsky, 2011; Shipton and Cowie

2001), with lower displacement faults typically having a smaller damage zone. However, field evidence has proved that fault thickness can vary by three orders of magnitude along the same fault, regardless of displacement value or host rock lithology (e.g. Shipton et al., 2006). Beach (1999) observed maximum damage zone values of 80 m in sandstone, even along faults with several hundred metres of displacement. Shipton and Cowie (2001) found that faults in sandstone had a damage zone width approximately 2.5 times that of the fault throw, though with the caveat that predicted damage zones could vary by about as much as 10-20% for any throw value. Knott et al. (1996) found damage zone widths in mixed lithologies in the hangingwall and footwall had different distributions, whilst still scaling with offset. Beach et al., (1999) and Antonellini and Aydin (1995) found that damage zones are narrower in finer-grained argillaceous rocks, but wider in coarser sandstones. Field observations from surface coal mines in Scotland show that fault damage zones hosted in Carboniferous carbonates such as limestones are typically fracture dominated, and extend over a larger area than those in sandstone, mudstone or coal (Figure 25). Damage zones are hypothesised to decrease in size with increasing depth, due to a presumed increase in the strength of rock surrounding the fault zone (e.g. Scholz, 2002). Other parameters such as associated diagenesis, depth of faulting and tectonic environment have been suggested as other factors responsible for scattering of data within the overall broad positive trend of fault displacement vs fault thickness (Choi et al., 2016).

Figure 25 Faulted McDonald limestone pavement exposed in the Spireslack surface coal mine, East Ayrshire. The faults and fractures here form part of a broader damage zone of an oblique-slip fault with 25 m displacement. The damage zone is composed of subsidiary synthetic faults, brittle fractures, and mineral veins.

2.5.2 Modelling damage zones beneath the Clyde Gateway area

The nature and width of fault damage zones beneath the Clyde Gateway area is not known with any certainty, as we have no field and only limited subsurface data. Mine plans from beneath the site accurately record the position, dip and often the throw of the faults, and their dip separation as they displace a coal seam, but there is no information on fractures relating to the faults on these plans. During mining ,coal would have extracted up to fault planes that significantly displaced the coals, and regardless of fracture content, and so mine plans cannot be used to determine damage zone width.

To model potential damage zone widths across faults in the Clyde Gateway area, data from fault widths in siliciclastic rocks from other studies are used (Beach et al., 1999; Shipton and Cowie, 2001; Fossen and Hesthammer, 2000; Shipton et al., 2006; Savage and Brodsky, 2011). The BGS Central Glasgow bedrock 3D model (Monaghan et al., 2013) is used to model likely damage zone widths around faults cutting the Carboniferous strata. The damage zone widths are applied based on the smallest likely damage zone width and the largest likely damage zone width, related to the average throw along the fault. For example, a fault with a recorded displacement of 10 m may have a damage zone as small as 1 m or as large as 100 m based on data from Fossen and Hesthammer (2000), Beach et al., (1999) and Shipton and Cowie (2001). For this study, the throws recorded along each fault in the Clyde bedrock model were arranged by order of magnitude (i.e. 1–10 m throw, 10–100 m throw, etc). Most fault throws fall between the range of 10 and 100 m, but the Shettleston and Dechmont faults have throws of over 100 m. Therefore, the likely ranges of damage zones for faults with throws of between 10 and 100 m, and 100 and 1000 m, are taken from existing data (see Table 4). Faults with throws of between 1 and 10 m were not included in the original 3D geological model but their ranges are included here also.

Source:	Shipton et al., 2006 (fault core and damage zones)		Beach et al., 1999 (damage zones)		Shipton and Cowie 2001 (damage zones)		Fossen and Hesthammer 2000 (damage zones)		Savage and Brodsky, 2011 (fault zone thickness)	
	Fault thickness ranges (m)									
Throw (m)	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
1-10	<10	50	0.3	30	5	35	10	50	n/a	n/a
10-100	6	100	1	100	25	>80	6	100	n/a	n/a
100-1000	0.7	100	5	n/a	n/a	n/a	50	n/a	5	100

Table 4 Fault thickness ranges organised by fault throw.

From these, the most likely ranges were taken and used for modelling damage zone widths within the Clyde Gateway area. For example, the data from Shipton et al. (2006) included undifferentiated fault core and damage zone width thicknesses: therefore the value of 0.7 m as a minimum thickness for damage zone width is not used as that is likely to be a data point from a fault core reading. The modelled widths are described in Table 5.

Throw (m)	**Modelled Widths (m)**
1-10 (not modelled in this study)	0.3 min, 50m max
10-100	1m min, 100m max
100-1000	5m min, 100m max

Table 5 Damage zone ranges used in damage zone thickness modelling of faults in the Clyde Gateway. See Table 4 for source data and section 2.5.2.1 for caveats.

For modelling purposes, the damage zone is represented by a copy of the originally modelled fault plane, placed at a distance of 100 m on either side of the original fault (see Figure 26 and Figure 27). All faults have been modelled with a maximum damage zone width of 100 m. Due to the resolution of the model, the minimum of 1 m wide for damage zones associated with faults of 10–100 m displacement faults has not been modelled, but the 5 m wide minimum for damage zones associated with faults with displacements of 100–1000 m has been modelled.

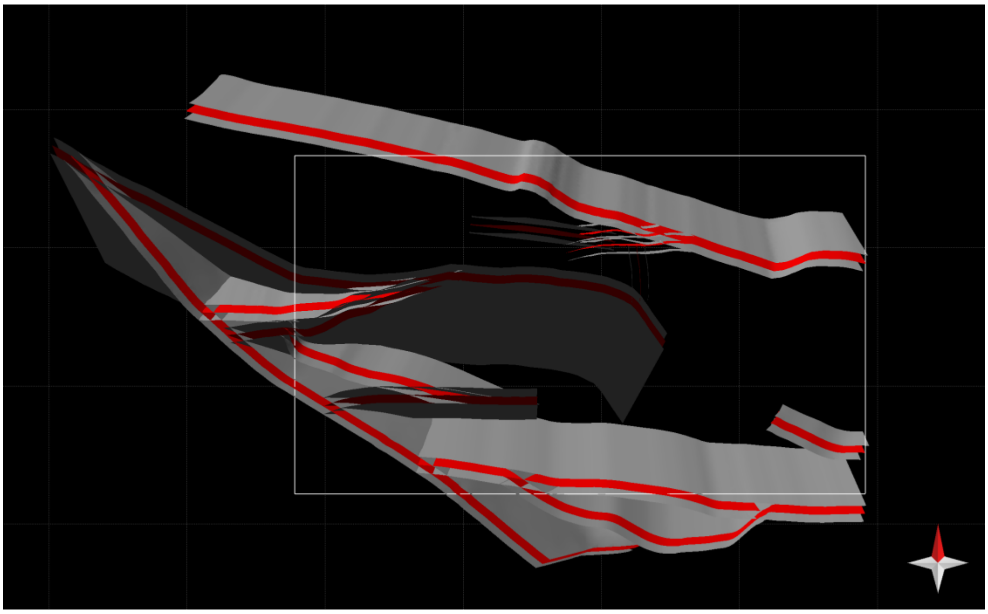


Figure 26: Damage zone limits modelled on either side of the existing fault network in the BGS 3D Clyde geological model. The originally modelled faults are coloured in red, and their maximum likely damage zone widths are in grey in both the hangingwall and the footwall of the fault. The rectangular outline of the Clyde Gateway area is included.

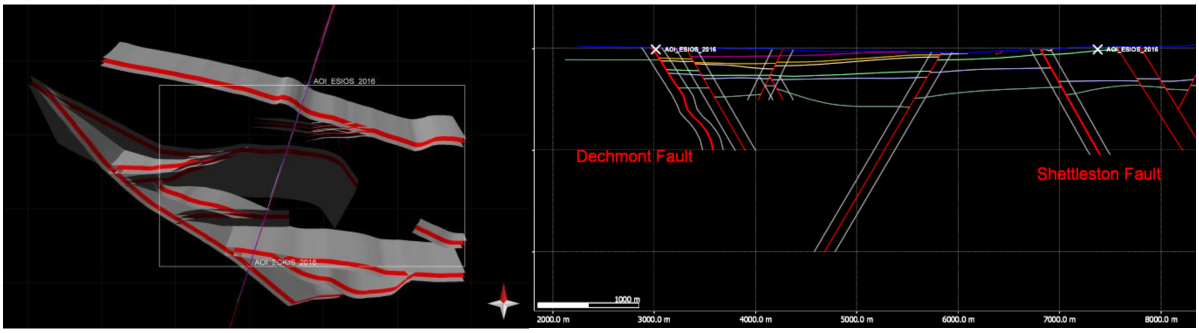


Figure 27: Cross-section across the Clyde Gateway area, intersecting the Dechmont Fault and the Shettleston Fault. Likely maximum damage zone widths are outlined in grey, on either side of the red fault plane.

2.5.2.1 Model caveats

The likely damage zone widths of a particular fault within the Clyde Gateway area are based on data collected from exhumed fault zones across the world. However, this maximum damage zone width value is *likely to exceed the true damage widths* of the faults in the Clyde Gateway area due to a number of factors:

- Damage zones are often asymmetric, with damage zones having different widths on either side of the fault. This asymmetry has been reported in many previous publications, and is partly attributed to the differing rock properties on either side of the fault, and to differing stress conditions in the fault walls (see review paper of Choi et al., 2016). For example, the hangingwall damage zone is more than three times wider than the footwall damage zone in the Moab Fault in Utah (Berg and Skar, 2005). The extent of damage in the footwall and hangingwall of faults in the Clyde Gateway area is not known; therefore further data are required to model the damage zones more accurately within the mixed lithologies in the Clyde Gateway area.
- Displacements along the faults in the Clyde Gateway area vary laterally, and with depth; it is likely therefore that the damage zone widths will vary along and down faults. Future work could focus on modelling damage zone widths with fault displacement along faults, and with depth.
- The influence of host rock lithology on damage zone width and type is not known within the Clyde Gateway area. Published research has shown that host rock lithology has an effect on both the width and nature of the damage zone: Beach et al., (1999) and Antonellini and Aydin (1995) found that damage zones are narrower in finer-grained argillaceous rocks, but wider in coarser sandstones. The damage zone maximum widths modelled in this study are based on research carried out predominantly in sandstone-hosted faults. However, the strata beneath the Clyde Gateway area are mudstone-rich, and in a mudstone hosted fault, it is possible that fault zone width will be narrower. Further data are required to model mudstone-hosted faults.
- Scholz (2002) hypothesised that damage zone width should narrow with depth due to a presumed increase in the strength of rock surrounding the fault zone. Whilst this has not been modelled here due to a lack of data, future work could investigate this aspect further.

Further caveats and questions related to the modelling of fault damage zones include:

- How do overlapping damage zones affect the widths and nature of the damage zones (e.g. Figure 28)? Is this area more intensely damaged than damage zones which are not linked?
- What effect will the damage zones have on hydraulic behaviour in the subsurface?

Future work should seek to address these problems specific to the Clyde Gateway area.

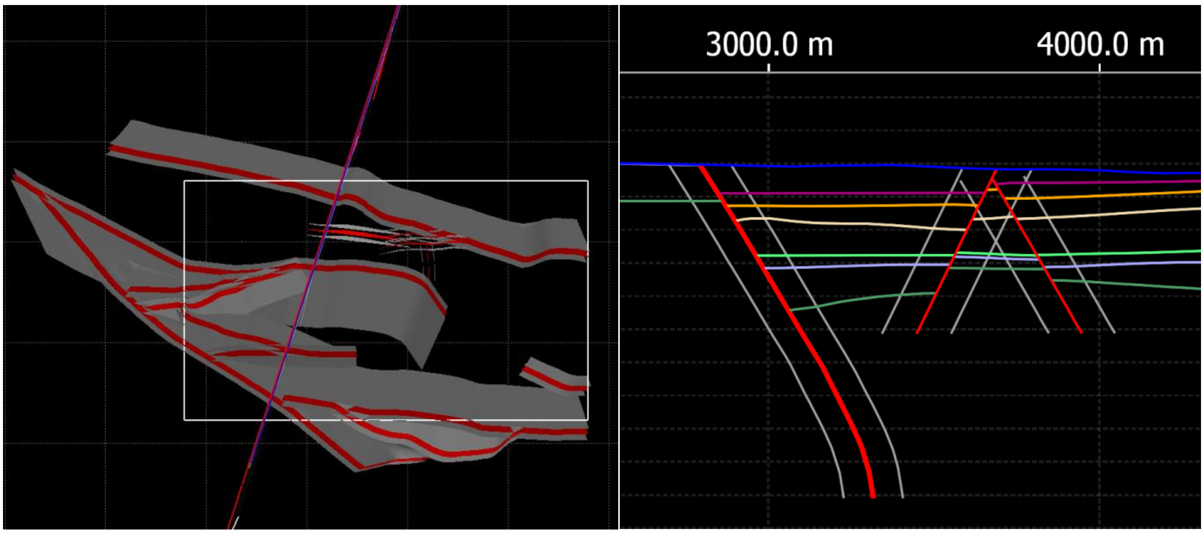


Figure 28 Example of overlapping damage zones within the Clyde Gateway area.

2.6 IN SITU STRESS

Understanding the geomechanics and stress state of the bedrock is important for any subsurface activity where the injection or extraction of fluid from the rock volume has the potential to change pore pressure. Changes in pore pressure have the potential to cause re-activation of fault structures or compaction.

Baptie (2010) and Baptie et al. (2016) describe current understanding of the stress field across central Scotland and the fact that there are no good stress data. In a regional context, faults striking east–west or east-north-east–west-south-west are considered to have a low reactivation potential, while faults striking north-east–south-west or north-west–south-east have the relatively highest reactivation potential based on the very limited existing dataset (Baptie et al., 2016). Site specific study and local data are required to assess further the potential for fault reactivation.

Stress is a six component tensor; however it can be simplified to four components for a stress field characterisation: vertical stress (S_v), minimum horizontal stress (S_{hmin}) and maximum horizontal stress (S_{HMax}) and stress field orientation. The relative magnitudes of these stress components vary depending on the fault environment (Table 6).

Faulting Environment	**σ1**		**σ2**		**σ3**
In normal faulting	S_v	≥	S_{HMax}	≥	S_{hmin}
In strike slip	S_{HMax}	≥	S_v	≥	S_{hmin}
In reverse faulting	S_{HMax}	≥	S_{hmin}	≥	S_v

Table 6 Summary of stress states associated with fault environments; after Zobach et al. (2003).

2.6.1 Stress Field Orientation

The stress field orientation typically defines the orientation of S_{HMax}, which is perpendicular to the orientation of S_{hmin}. Borehole breakouts which define the orientation of S_{hmin} can be identified using imaging tools and 4-Arm calipers (Reinecker et al., 2003; Tingay et al., 2008; Kingdon et al. 2016). The Bargeddie 1 well has 4-Arm Caliper data, but no borehole imaging. Kingdon et al. (2016) showed that the use of imaging tools over 4-Arm caliper data can reduce uncertainties in the stress field orientation. Given the lack of borehole imaging data, however, no study of the stress orientation has been attempted

2.6.2 Vertical Stress

The vertical stress is often used to predict fracture gradients and pore pressure in the absence of in situ data (Tingay et al., 2003). It has been documented in multiple studies that the state of stress can be highly variable and where possible the vertical stress should be determined using in situ data (Tingay et al., 2003; Williams et al., 2015, 2016; Verweij et al., 2016).

Vertical stress can be calculated using density logs, after the method of Zoback et al. (2003). This method integrates measurements from density logs from the surface to the area of interest - the total depth of the well in this case. Using Equation 1:

$$S_v = \int_0^z \rho(z) g \, dz \approx \bar{\rho} g z \qquad (1)$$

where $\bar{\rho}$ is the mean overburden density, $\rho(z)$ is the density as a function of depth and g is the acceleration due to gravity. Figure 29 shows the two wells in the greater Glasgow area, Bargeddie 1 and Maryhill, for which data are available.

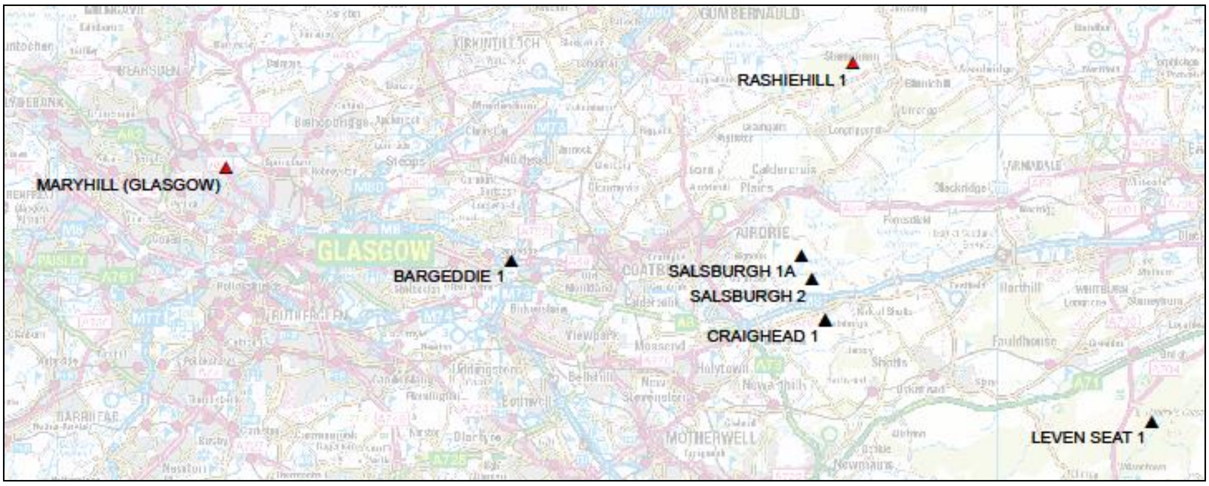


Figure 29 Location of wells in the Glasgow area with data that could be used to calculate vertical stress from density logs. Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2017. Licence number 100021290 EUL

Maryhill has a total depth (TD) of 306 m with a density log from 55 m. Bargeddie 1 has a density log from 440 m to 1040 m. To calculate the vertical stress for Bargeddie 1 the density had to be estimated from 0–440 m. The density from ground level to 55 m was assigned a value of 2.1 G/CC. From 55–440 m an average density was calculated using the density from Maryhill (2.57 G/CC). The vertical stress gradient for Bargeddie 1 calculated using this method is 25 MPa km^{-1}.

2.6.3 Minimum Horizontal Stress

The minimum horizontal stress (S_{hmin}) is also the minimum principle stress ($\sigma 3$) in both normal and strike slip environments. Baptie (2010) demonstrated that the UK is predominately a strike slip / reverse environment with north-west–south-east compression driven by the Mid-Atlantic Ridge. The minimum horizontal stress can be estimated from formation integrity tests or leak off tests. Extended leak off tests are required to determine the value of S_{hmin}(XLOT's). There are no XLOT's available for this area and only one leak off test from Bargeddie 1 which is not sufficient to estimate the magnitude of the minimum horizontal stress.

2.6.4 Maximum Horizontal Stress

The data required to quantify a maximum horizontal stress (e.g. tensile strength, compressive strength, reservoir pressure, minimum horizontal stress) was not located in the available datasets and no legacy hydraulic fracturing or overcoring data have been found in the area.

3 Superficial deposits

3.1 OVERVIEW

A complex succession of superficial deposits covers the Clyde Gateway area, including widespread glacial till and marine, lacustrine and fluvio-glacial deposits, overlain by fluvial deposits, recent alluvium and anthropogenic deposits (Figure 30, Table 7; see also Monaghan et al., 2013). There is also widespread made, filled and landscaped ground (Figure 30).

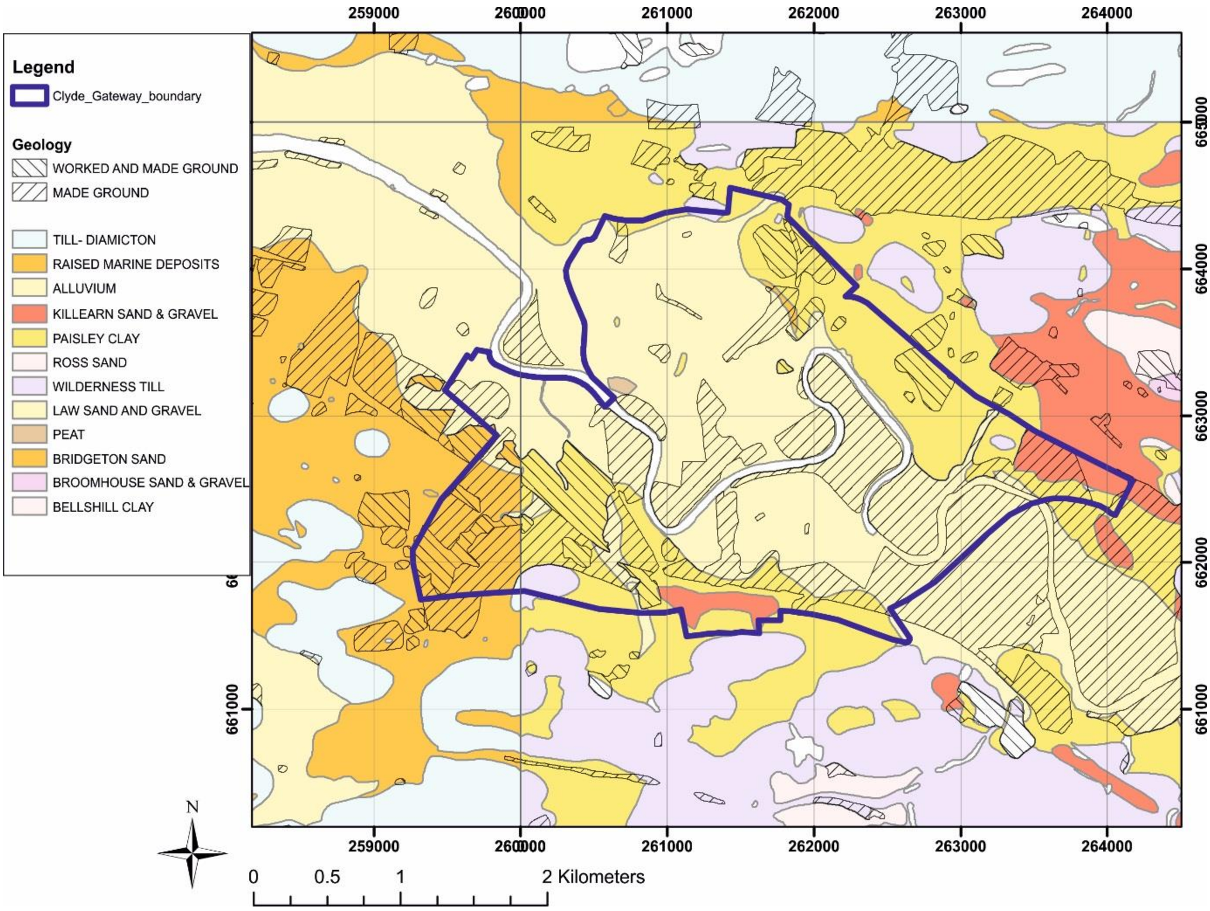


Figure 30 Clyde Gateway area summary of superficial geology from BGS©NERC 2016 DigMap 1:10 000-scale data.

Code	Geological Unit	Equivalent description on 1: 10, 000 scale published map
Water	Water	Unattributed polygons or underlying sediments described
MGR-ARTDP	Made Ground (made and worked ground undifferentiated)	Made Ground (MGR), Made Ground and Worked Ground (WMGR), Infilled Ground (WMGR)
PEAT-P	Peat	Peat – blanket or basin peat, Flandrian (PEAT)
LAWSG-XCZSVP	Law Sand and Gravel Member	Alluvium – modern river floodplains – located along the upper reaches and tributaries to the River Clyde, Flandrian (ALV). Also includes some Alluvial Fan Deposits, Flandrian (ALF) and some River Terrace Deposits, Flandrian (RTD1 and RTD2)
GOSA-XCZSV	Gourock Sand Member	Marine Deposits – located along the lower reaches of the River Clyde, Flandrian (MDU) and Alluvium – modern river floodplains – along the upper reaches of the River Clyde, Flandrian (ALV)
KARN-XSV	Killearn Sand and Gravel Member	Generally Raised Marine Deposits, Devensian (RMDV), Raised Marine Deltaic Deposits, Devensian (RMDDD) or Raised Marine Intertidal and Subtidal Deposits, Devensian (RMIS)
PAIS-XCZS	Paisley Clay Member	Generally Raised Marine Deposits, Devensian (RMDV) or Raised Marine Intertidal and Subtidal Deposits, Devensian (RMIS)
BRON-XSVZ	Bridgeton Sand Member	Largely concealed beneath younger deposits, where present, exposures usually represented as Raised Marine Deposits, Devensian (RMDV)
RSSA-XSV	Ross Sand Member	Glaciolacustrine Deposits, Devensian (GLLDD), Glaciolacustrine Deltaic Deposits, Devensian (GLDDD) or Glaciofluvial Deposits, Devensian (GFDUD)
RSSA-XSZ	Ross Sand Member (silt, sand)	Largely concealed beneath younger deposits, identified at depth from borehole data, rare exposures represented as Glaciolacustrine Deposits, Devensian (GLLDD) or Glaciolacustrine Deltaic Deposits, Devensian (GLDDD)
BHSE-XSV	Broomhouse Sand and Gravel Formation (sand and gravel)	Largely concealed beneath younger deposits, where present, exposures usually represented as Glaciofluvial Deposits, Devensian (GFDUD), but also as Glaciofluvial Ice-Contact Deposits, Devensian (GFICD)
BHSE-S	Broomhouse Sand and Gravel Formation (sand)	Not recorded on the maps in the Clyde Gateway area (concealed beneath younger deposits), identified at depth from borehole data
WITI-DMTN	Wilderness Till Formation	Till - Devensian (TILLD)
CADR-XSV	Cadder Sand and Gravel Formation	Generally concealed beneath younger deposits, identified at depth from borehole data, rare exposures represented as Glaciofluvial Deposits, Devensian (GFDUD)
SUPD-XSV	Sand and gravel	Not recorded on the maps in the Clyde Gateway area (concealed beneath younger deposits), identified at depth from borehole data

Table 7 Summary of lithostratigraphic units differentiated in the 3D superficial deposits geological model based on borehole and 1:10 000-scale map data. X indicates that each lithology is represented (e.g. XSV is a unit containing sand and gravel as opposed to SV which would be gravelly sand), where C=clay, Z=silt, S=sand, V=gravel, DMTN=diamicton, ARDP=artificial deposits, P=peat

3.2 BOREHOLES, MAP DATA

The majority of the 3400 borehole records BGS holds (includes site investigations and trial pits) within the Clyde Gateway area penetrate to depths of less than 30 metres and define the complex artificial and superficial deposit succession (see Figure 30).

BGS-published superficial deposits map data include the NS66SW 1:10 000-scale geological map (2007 - revised after initial modelling), the NS56SE 1:10 000-scale geological map (2007 - not including revisions from subsequent modelling). BGS 1:50 000 scale map sheets 30E Glasgow (1994 superficial deposits) and 31W Airdrie (1992 superficial deposits). BGS Memoirs form a definitive reference source for the geology of this area (Hall et al., 1998, Forsyth et al., 1996). Map data is available as GIS shapefiles (DigMapGB) or as scans (Mapviewer).

Key publications on the superficial deposits geology of the region include Browne and McMillan (1989), descriptions in Hall et al., (1998), Forsyth et al. (1996) and more recently by Finlayson et al. (2010).

3.3 GSI3D (DETERMINISTIC) MODELLING

The Clyde Gateway area falls within the previously published ‘Central Glasgow’ model (Merritt et al., 2009; Monaghan et al., 2013). This model has been updated between the coordinates SW corner 258000, 660850, NE corner 265000, 665000 (an area approximately 7 km x 4 km) to include all boreholes drilled since 2005 (Figure 31).

The model was completed using GSI3D© software (Kessler et al., 2008). This involves correlating the various geological units through borehole logs in 2D cross-sections; the cross-sections intersect to form a connected network across the model area. The correlated sections and geological map data provide information on the lateral distribution of each geological unit which is saved as an ‘envelope’ for each geological unit. Together, the envelopes and sections are used to model each of the geological units in 3D.

3.3.1 Updating the superficial deposits model

The approach taken to update the model in 2016 was to focus on updating existing section line interpretations and adding new section lines in parts of the area with new borehole data. This improved the detail and certainty in parts of the model.

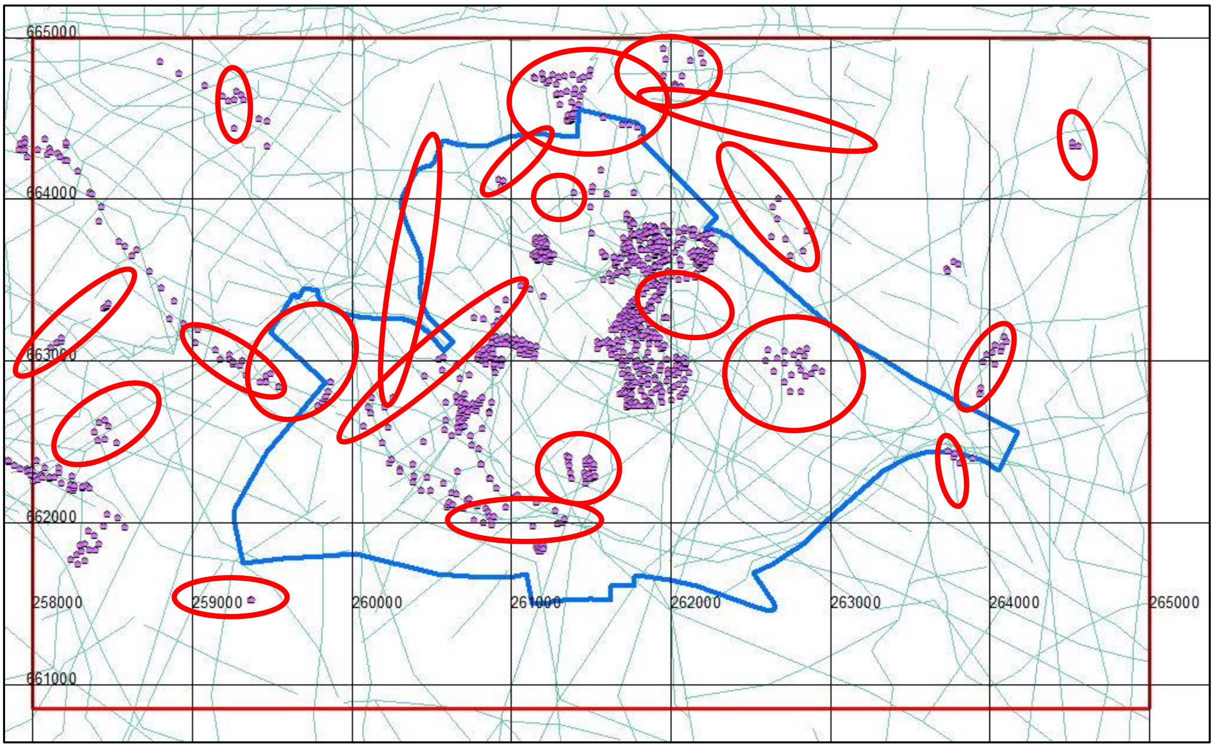


Figure 31 Existing GSI3D section lines (green) from the previous Central Glasgow model, location of boreholes entered into the BGS databases post-2005 (purple) and areas of the model updated (red circles).

The post-2005 boreholes were used to update the model in the following ways:

- **Added into existing sections** – existing sections were re-routed to include additional boreholes where possible
- **Used to create a new section** – new sections were created or existing sections extended if there was not an existing section close to the additional boreholes. New sections were always extended to cross existing sections so the geological units could be tied-in with the existing network of sections.
- **Projected into existing sections** – where an existing section passed through a large number of additional boreholes spread along its length, the most appropriate approach was to project boreholes that were close into the existing section and adjust the geological linework as necessary. This approach quickly improved existing sections without the need to re-draw the section.
- **Informed the presence or absence of a unit across the model** – away from the lines of section the additional boreholes provide a constraint when drawing the geological unit 'envelopes' which show the lateral extent of a unit

Changes were also made to any crossing sections where necessary and edits were made to the associated geological envelopes, where required. A metadata report (Arkley, 2017) provides more information on the superficial deposits model.

Following the editing of sections and envelopes across the Clyde Gateway area, the model was calculated (Figure 32). Grids for each geological unit were exported (25 m cell size) to GIS along with information such as boreholes used and lines of section. A rockhead grid was also calculated and exported for use in the bedrock model (Figure 33).

Due to improvements in software, availability of additional data and external requirements the superficial deposits model has been altered and updated several times since its original development. As a result the model may have legacy inconsistencies (Arkley, 2017 gives more detail). .

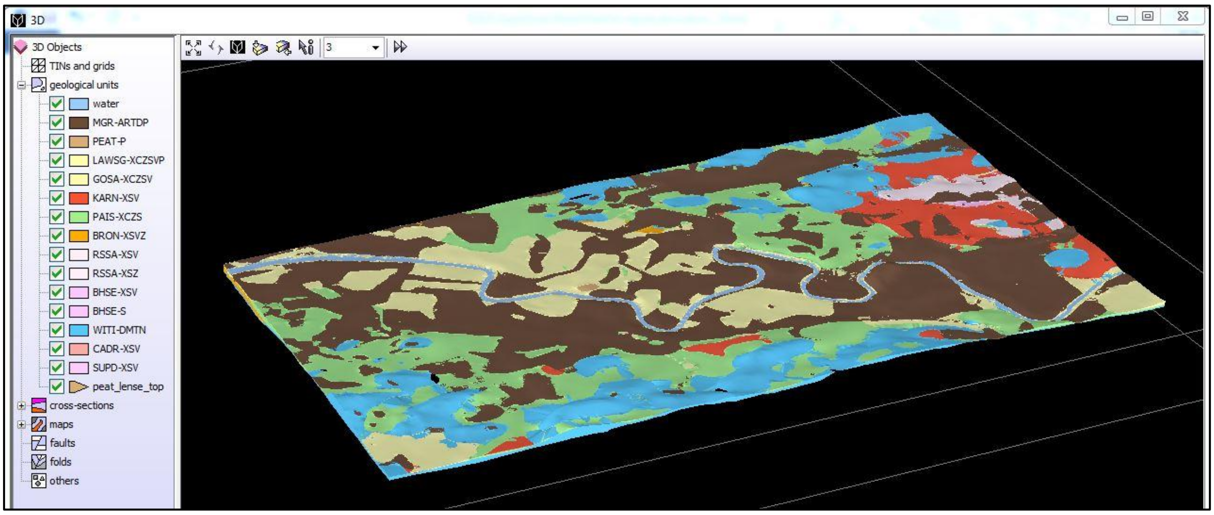


Figure 32 Overview of the superficial deposits model across the Clyde Gateway area, looking north-east, three times vertical exaggeration.

The 3D superficial deposits model contains 15 subdivisions and is of use in borehole prognosis, site planning and in a hydrogeological conceptual model (Figure 46 below). For example, the modelled rockhead surface shows significant variability across the area from -40 m to +36 m relative to Ordnance Datum (O.D., Figure 33). Artificial (made) ground is not subdivided.

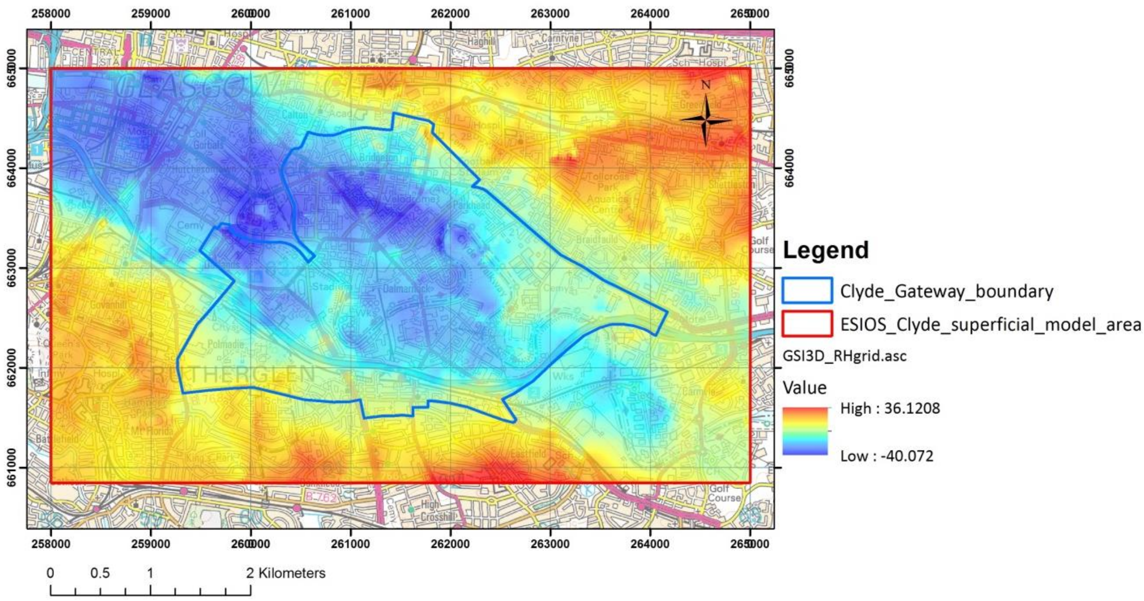


Figure 33 Rockhead surface for the Clyde Gateway area generated by combining the bases of the modelled superficial deposits. Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2017. Licence number 100021290 EUL

3.4 STOCHASTIC MODELLING

Automated stochastic modelling techniques have been used to develop predictive lithology and property models for glacial and fluvial deposits in Glasgow (Kearsey et al., 2015). A moderate improvement in the prediction of lithology when using a lithologically-derived stochastic model compared with a conventionally interpolated lithostratigraphic model is documented (Kearsey et al., 2015). In addition, simulated lithofacies distributions were also used as input in a flow model for numerical simulation of hydraulic head and groundwater flux using the Glasgow area (Bianchi et al., 2015). Future work could further utilise and develop these techniques to inform borehole prognoses and hydrogeological characteristics for GGERFS.

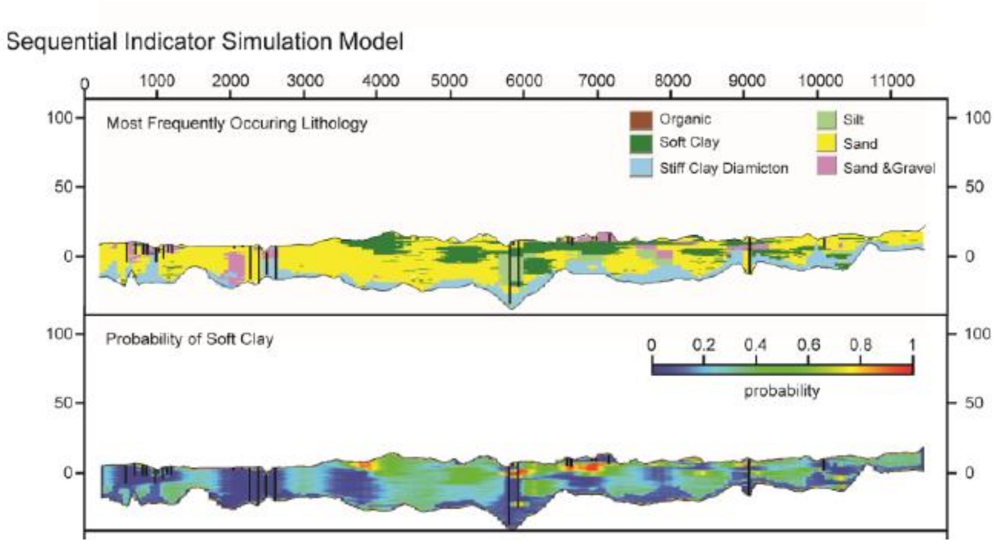


Figure 34 Example of a cross-section showing the sequential indicator simulation model most frequently occurring lithology and the probability of the presence of separate lithologies from the stochastic model, reproduced with permission from Kearsey et al. (2015). The black lines mark the positions of the geotechnical boreholes used to create the model.

4 Hydrogeology

4.1 INTRODUCTION

4.1.1 Background

Current knowledge of the hydrogeology of the Clyde Gateway area (through which the River Clyde flows) and its surrounding area (Figure 35), including knowledge of aquifer properties and groundwater processes and systems, is summarised below, including:

- a review of existing hydrogeological information (e.g. aquifer properties and groundwater levels, quality and temperature);
- a preliminary 3D conceptual model of the hydrogeology of the Clyde Gateway area; and
- a discussion of the requirements for monitoring to establish baseline conditions and detect environmental changes resulting directly or indirectly from future development.

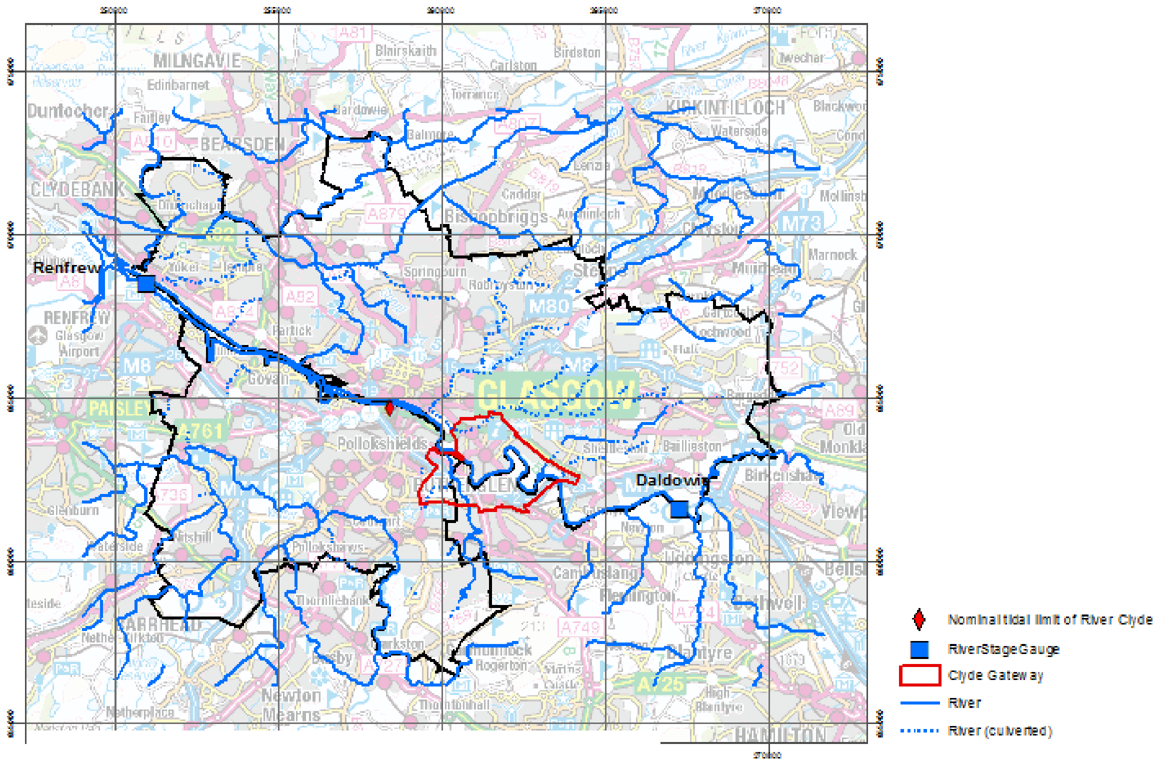


Figure 35 Glasgow City Council boundary in black; Clyde Gateway area including part of South Lanarkshire Council area; River Clyde and tributaries; location of River Clyde stage gauges (river level monitoring gauges, operated by SEPA) and nominal tidal limit. Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2017. Licence number 100021290 EUL

4.1.2 Surface water

The River Clyde is the main surface water course in the area, flowing approximately east to west through the Clyde Gateway area towards the Clyde estuary (Figure 35). The Clyde Gateway is upstream of the weir that marks the nominal tidal limit of the River Clyde. At least two river stage gauges are operated by SEPA in Glasgow: one upstream at Daldowie and one downstream at Renfrew (Figure 35). A number of tributaries flow into the River Clyde in the Clyde Gateway; these are largely culverted (Figure 35).

4.1.3 Geology – summary

The Clyde Gateway area, as with most of Glasgow, is underlain by a heterogeneous sequence of Quaternary sediments of glacial, estuarine/marine and alluvial origin, which are up to ~35 m thick. Below this, the uppermost bedrock unit is the sedimentary Carboniferous Scottish Coal Measures Group, which comprises a repetitive sequence of sandstone, siltstone, mudstone, shale, coal and ironstone.

The natural geological sequence in the Clyde Gateway area is overlain by extensive anthropogenic deposits, which are highly variable in origin, nature and thickness, including worked, infilled, landscaped and disturbed ground. Artificial ground in Glasgow is generally less than 2.5 m thick, but in the most industrialised areas are frequently up to 10 m thick, and less frequently more than 20 m thick (Monaghan et al., 2014).

4.1.4 Groundwater bodies

SEPA classify and regularly assess the status of bedrock and superficial groundwater bodies. The Clyde Gateway area lies on the Glasgow and Motherwell bedrock groundwater body; and three superficial groundwater bodies: the Glasgow Sand and Gravel; Carmyle and Tollcross Sand and Gravel; and Govan Sand and Gravel groundwater bodies. The current status of these groundwater bodies is shown in Table 8 (source: http://www.environment.scotland.gov.uk/get-interactive/data/groundwater/).

Groundwater body	Bedrock/Superficial	Quantitative Status (2016)	Chemical Status (2016)
Glasgow and Motherwell	Bedrock	Poor	Poor
Glasgow Sand and Gravel	Superficial	Good	Good
Carmyle and Tollcross Sand and Gravel	Superficial	Good	Good
Govan Sand and Gravel	Superficial	Good	Poor

Table 8 Groundwater bodies in the Clyde Gateway area and their current status

4.2 BEDROCK (CARBONIFEROUS SEDIMENTARY) HYDROGEOLOGY

This section describes the hydrogeology of Carboniferous sedimentary aquifers in general in the Glasgow area. There is limited evidence to characterise the bedrock hydrogeology of Glasgow, and it remains poorly understood. It is expected to be internally complex and to show complex interaction with groundwater in overlying superficial deposits and surface waters.

4.2.1 Background information (not specifically for the Clyde Gateway area)

Carboniferous sedimentary rocks in the Central Belt typically form multi-layered and vertically segmented aquifers. The typically fine-grained, well-cemented rocks have low intergranular porosity and permeability, and groundwater flow and storage dominantly occur in fractures in the rock. Hydraulic aquifer properties therefore depend largely on the local nature of fracturing in the rock (Ó Dochartaigh et al., 2015). The rocks tend to form moderately productive aquifers (Ó Dochartaigh et al., 2015). Measured matrix porosity values are in the range 12–17%; hydraulic conductivity (permeability) values are in the range 0.003–0.1 m/d; and transmissivity values are in the range of 10–1000 m^2/d (Table 9).

Sandstone units within the sedimentary sequence generally have the highest transmissivity and storage capacity, and therefore tend to act as discrete aquifer units, interspersed by lower permeability siltstones, mudstones and (undisturbed) coal seams. Limestone beds have variable permeability, but are generally thin in comparison with the whole aquifer sequence, and so their overall impact on groundwater flow is generally only significant on a local scale (Ó Dochartaigh et al. 2015).

Groundwater can be present in the aquifer under unconfined or confined conditions, which can vary between different sandstone and other sedimentary units and at different depths. Groundwater heads likewise vary between different aquifer layers (Ó Dochartaigh et al. 2015).

Groundwater flow paths through the aquifer are thought to be complex, due to their naturally layered nature, which tends to promote preferential horizontal flow, and the predominance of fracture flow (Figure 37). Flow paths are likely to be relatively deep (100s of metres) and long (1–10 km) (Figure 37). Previous assessments have thought that Glasgow acts as the focal point for much of the groundwater discharge from Carboniferous aquifers from the Central Coalfield area, with prevailing groundwater flow paths from the east, north-east and south-east (Hall et al., 1998). There is, however, a lack of measured hydrogeological data from Glasgow to support this hypothesis.

Faults can divide the sedimentary sequence vertically. Little direct evidence is available for the hydraulic nature of the faults: some may be permeable, acting as a preferential flow pathways; others may act as barriers to groundwater flow (Ó Dochartaigh et al., 2015; Figure 37).

4.2.2 Impacts of mining

Mining in Carboniferous sedimentary rocks has significantly changed natural hydrogeological conditions. Mine voids (shafts and tunnels) can artificially and greatly increase aquifer transmissivity, sometimes across large areas and depths (to ~1 km), and can link formerly separate groundwater flow systems both laterally and vertically (Figure 38). Aquifer storage can also be locally increased. Even where mine voids have subsequently collapsed, deformation of the surrounding rock mass is likely to cause further changes in transmissivity and, to a lesser degree, storage (Younger and Robins, 2002). Parts of former mine workings have been infilled, which may cause further diversions in groundwater flow, leading to groundwater discharge and/or chemical degradation in unexpected places.

Quantitative aquifer properties data from test pumping are rare for boreholes intercepting former mines. However, records of specific capacity from boreholes drilled in aquifers which have been extensively mined, many of which intercept mine workings, give an indication of the range in aquifer properties and how this varies from the unmined aquifers; and there are many records of yields from mine dewatering boreholes (Table 9). The higher yield and specific capacity values for these boreholes are likely to reflect the productivity of Carboniferous aquifers subject to extensive coal mining.

Groundwater flow paths are likely to be even more complex in mined aquifers than in undisturbed Carboniferous aquifers.

Mine dewatering – by abstraction of groundwater from boreholes penetrating mineworkings – continued throughout mining activities, which finally ended in the 1980s in the Glasgow area (BGS data). After mine dewatering ceased, it is likely that groundwater levels in former workings will have risen. As far as BGS is aware, there are few or no recorded problems caused by rising groundwater levels in Glasgow, but this may be partly a consequence of the lack of monitoring of, or data on, groundwater levels in bedrock.

4.2.3 Groundwater chemistry

There is little recent information on groundwater chemistry in the Carboniferous sedimentary aquifer in Glasgow. Some information is available from across central and southern Scotland from the Baseline Scotland project (
Table 10). The natural chemistry of groundwater in Carboniferous sedimentary aquifers is often moderately to highly mineralised. Groundwaters in the Coal Measures and Clackmannan groups are typically more mineralised than in the Inverclyde and Strathclyde groups. A detailed description of the chemistry of groundwater in these different Carboniferous groups across the Midland Valley is given in Ó Dochartaigh et al. (2011). A summary for all Carboniferous aquifers is provided in
Table 10 and for individual groups in Box 1.

Groundwater quality is also affected by mining. Groundwater discharges from mine workings are typically strongly mineralised, with high specific electrical conductivity (SEC) and particularly high concentrations of HCO_3, Ca, SO_4, Fe and Mn, and low in dissolved oxygen. The pH values are generally well buffered and alkalinity is high, indicating significant reaction with carbonate material in the aquifers (Ó Dochartaigh et al., 2011). Acid mine water discharge is not currently a known problem in Glasgow, and investigations at a number of sites showed good quality groundwater in abandoned mine workings (Glasgow City Council, pers. comm.).

Groundwater residence times are often in excess of 60 years (Ó Dochartaigh et al., 2011).

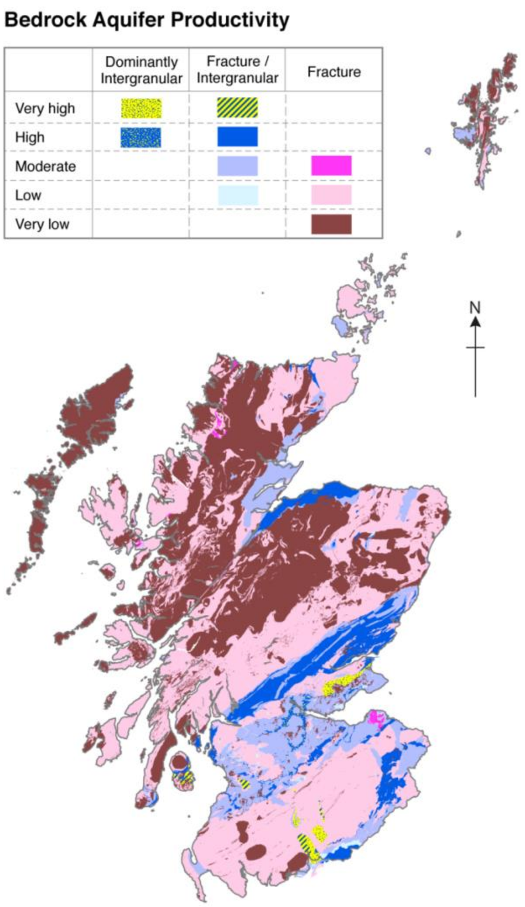


Figure 36 Bedrock aquifer productivity in Scotland. Carboniferous sedimentary rocks in the Central Belt are dominantly moderately productive, with mixed fracture/intergranular flow.

Table 9 Summary of available aquifer properties data for Carboniferous sedimentary aquifers: (top) not extensively mined for coal; (bottom) extensively mined for coal. From Ó Dochartaigh et al. (2015).

	Porosity (%)	Matrix hydraulic conductivity (m/d)	Transmissivity (m^2/d)	Specific capacity (m3/d/m)	Operational yield (m^3/d)
Carboniferous aquifers – not extensively mined for coal	12–17 (34)	0.0003–0.1 (37)	10–1000 * (5)	48–132 * (46) (minimum 0.43; maximum 1320) *	131–418 (348)

	Porosity (%)	Matrix hydraulic conductivity (m/d)	Transmissivity (m^2/d)	Specific capacity ($m^3/d/m$)	Operational yield (m^3/d)
Carboniferous aquifers – extensively mined for coal			10–1000 * (5)	48–132 * (46) (minimum 0.43; maximum 1320) *	1987–3279 (171) (minimum 41; maximum 22 248)

* May refer to both mined and nonmined aquifers
Ranges of values refer to mean and median values except where indicated
Number of values indicated in brackets
Data from the British Geological Survey

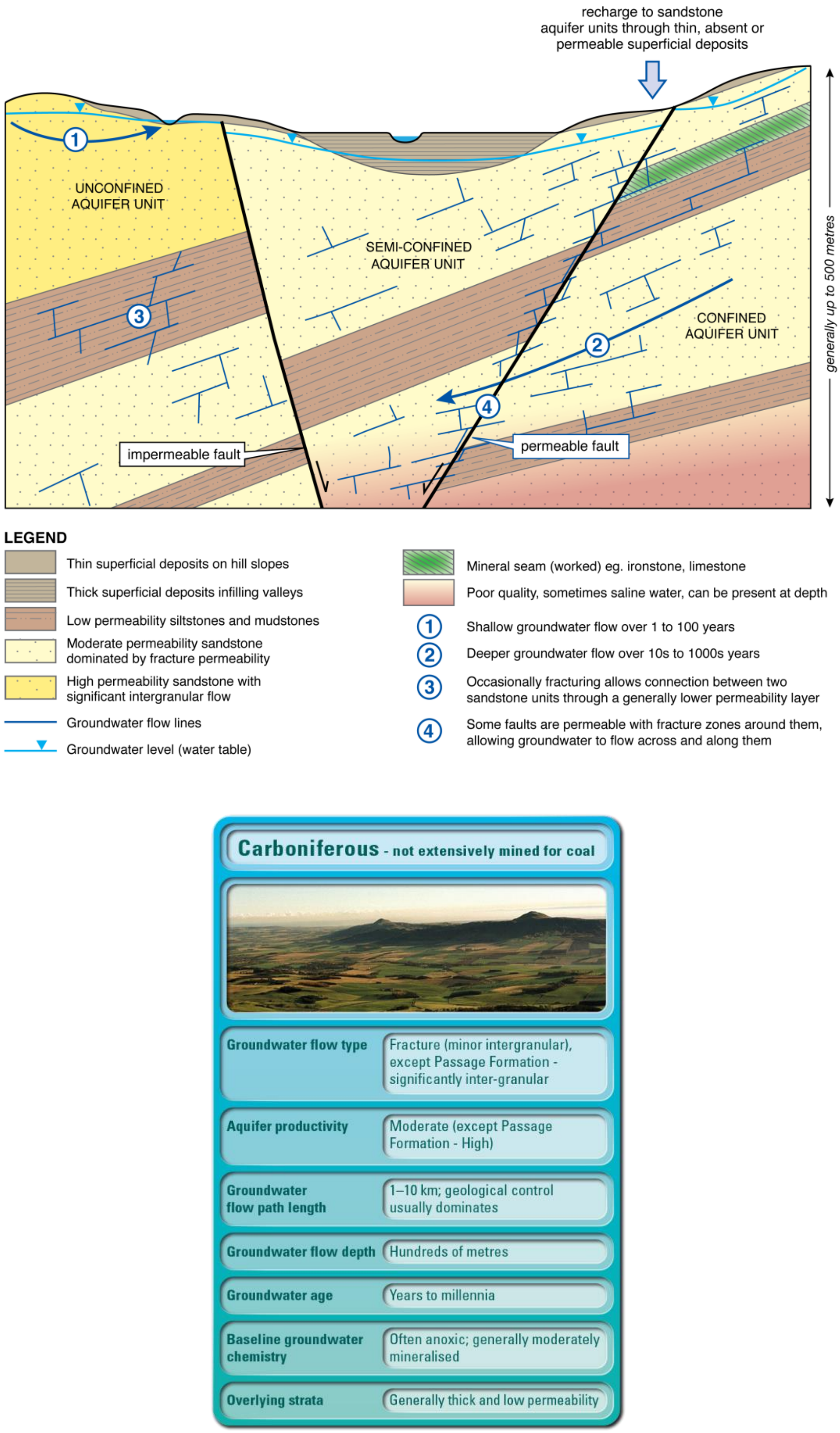
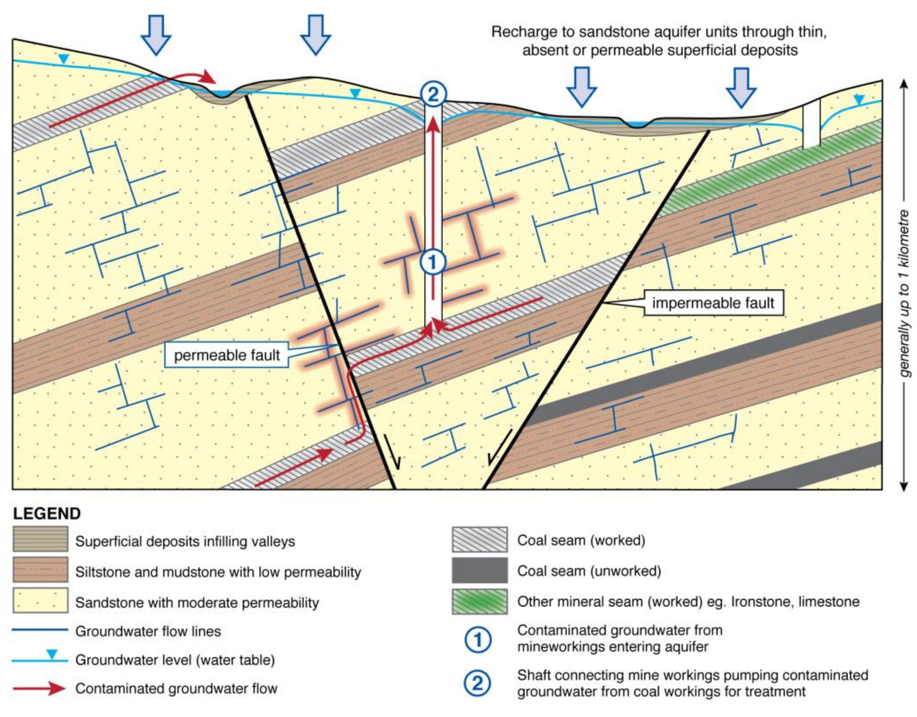


Figure 37 Overview of the hydrogeology of Carboniferous aquifers in Scotland that have not been extensively mined for coal: (top) schematic cross-section; (bottom) summary of aquifer characteristics. From Ó Dochartaigh et al. (2015).



Carboniferous - extensively mined for coal

Groundwater flow type	Fracture (minor intergranular)
Aquifer productivity	Moderate
Groundwater flow path length	1–10 km; dominated by impacts of historical mining
Groundwater flow depth	Hundreds of metres +
Groundwater age	Months to millennia
Baseline groundwater chemistry	Often anoxic; generally moderately to highly mineralised
Overlying strata	Generally low permeability. Thick in valleys, thinner elsewhere

Figure 38 Overview of the hydrogeology of Carboniferous aquifers in Scotland that have been extensively mined for coal: (top) schematic cross-section; (bottom) summary of aquifer characteristics. From Ó Dochartaigh et al. (2015).

Table 10 Summary of baseline chemistry of Carboniferous sedimentary aquifers in Scotland: (top) not extensively mined for coal; (bottom) extensively mined for coal. From Ó Dochartaigh et al. (2015).

Element	Units	n[a]	n <dl[b]	$P_{0.1}$	$P_{0.25}$	$P_{0.5}$	$P_{0.75}$	$P_{0.9}$
Ca	mg/L	55	0	35.5	43.8	58.7	76.2	154
Cl	mg/L	54	0	9.67	18.1	36.8	52	98.8
DO_2	mg/L	21	0	0.8	1.85	2.76	6.11	9.3
Fe	µg/L	52	9	3	6	46	300	921
HCO_3	mg/L	54	0	166	213	256	318	382
K	mg/L	54	0	1.4	2.08	4.42	7.75	9.48
Mg	mg/L	55	0	12.2	18.9	27.2	36.7	53.3
Na	mg/L	55	0	6.58	12.4	27.9	51.8	146
NO_3 as NO_3	mg/L	36	8	0.04	0.07	3.21	17.24	30.98
pH		50	0	6.69	7.02	7.3	7.68	8.04
SEC	µS/cm	50	0	353	516	694	976	1450
SO_4	mg/L	55	0	5.03	22	38.5	74.6	175

Element	Units	n[a]	n <dl[a]	$P_{0.1}$	$P_{0.25}$	$P_{0.5}$	$P_{0.75}$	$P_{0.9}$
Ca	mg/L	56	0	30.9	41.5	71	113	245
Cl	mg/L	56	0	10.7	14.4	23.4	63.4	1140
DO_2	mg/L	36	4	NA	0.3	1.2	2.99	5.96
Fe	µg/L	54	0	31.3	106	675	3730	9360
HCO_3	mg/L	54	0	100	206	324	467	581
K	mg/L	54	0	1.51	2.52	4.26	11.3	26.3
Mg	mg/L	56	0	7.42	15	28.2	48	102
Na	mg/L	56	0	11	13.2	27.6	132	519
NO_3 as NO_3	mg/L	52	24	0.04	0.09	0.13	1.33	8.84
pH		52	0	6.3	6.58	7	7.46	7.69
SEC	µS/cm	52	0	311	470	740	1240	1700
SO_4	mg/L	56	0	10.8	32.9	73	118	270

[a] number of samples
[b] number below detection limit

Box 1 A summary of groundwater chemistry in Carboniferous sedimentary aquifer units in the Midland Valley (from Ó Dochartaigh et al. 2011)

Coal Measures Group

Groundwaters from the Coal Measures Group are generally of bicarbonate type, with cations either dominated by Na or with no dominant cation. Average alkalinity values are the highest of all the hydrogeological units sampled, including the 'Mine' waters. There is a large range in SEC values and the median value is the highest for all the groups except 'Mine' waters. The waters are generally anoxic and slightly acidic to near-neutral. The groundwaters typically have moderate concentrations of the major cations Ca, Mg, Cl and SO_4, and high concentrations of Na relative to the other aquifer groups. In most cases the calcite saturation index showed the groundwaters were close to saturation. There is a large range in Fe and Mn concentrations but concentrations are usually high, with the highest average of any group except the 'Mine' waters.

Clackmannan Group

Groundwaters from the Clackmannan Group are generally either of Ca-Mg-HCO_3 type Na or have no dominant anion; a few show a cationic dominance of Na. The groundwaters typically have high HCO_3 concentrations, a near-neutral pH, and generally low dissolved oxygen. SEC values show a wide range but a moderate average. The waters generally have moderate to high concentrations of the major cations Ca, Mg, Ba and Cl. Concentrations of SO_4 were the highest of all the hydrogeological units except 'Mine' waters. Most of the samples were significantly undersaturated with respect to calcite. Concentrations of Fe and Mn were moderate to high, with variability due to the redox conditions in the aquifer.

Inverclyde Group

Most of the groundwaters from the Inverclyde Group were of Ca-HCO_3 type. They typically have moderate HCO_3 with a near-neutral pH. Dissolved oxygen concentrations are generally low but most of the waters are not anoxic. SEC values are typically moderate. The groundwaters typically have relatively low concentrations of the cations Na, Cl and SO_4 and moderate concentrations of Ca and Mg. In most cases the calcite saturation index showed the groundwaters were close to saturation. Concentrations of Fe and Mn are typically relatively low, reflecting the generally oxic nature of the groundwaters from this group.

Strathclyde Group

Most of the groundwaters sampled from the Strathclyde Group were of Ca-Mg-HCO_3. Some samples are more dominated by Na with no anionic dominance. The groundwaters typically have moderate HCO_3 concentrations with near-neutral pH. Dissolved oxygen concentrations are usually low but most of the waters are not anoxic. SEC values are generally moderate to high. The waters typically have moderate concentrations of the cations Ca, SO_4, Na, Cl and Mg. In about half of the samples the calcite saturation index showed the groundwaters were close to saturation or saturated with respect to calcite; the other half were undersaturated. Iron concentrations are relatively low on average but show a wide range. Mn concentrations are typically moderate.

4.2.4 Bedrock hydrogeology: data specifically for Glasgow/Clyde Gateway

The known availability of bedrock aquifer properties data is summarised in Table 11 and Figure 39. The known availability of bedrock groundwater level data is summarised in Table 12

There are no analyses of Carboniferous groundwater chemistry measurements in Glasgow in the Baseline Scotland (O Dochartaigh et al., 2011) dataset.

- There are two known analyses within ~5 km of the city boundary.
- There are no known existing boreholes in bedrock in Glasgow that are monitoring groundwater levels or chemistry. SEPA have indicated the presence of a limited number of local site monitoring of bedrock hydrogeology and this will be investigated further.
- BGS has no records of historical mine dewatering from boreholes in the Clyde Gateway. We have 14 records within ~20 km of the Clyde Gateway, all but two from boreholes that finished abstracting from collieries between 1948 and 1968; and two that continued until 1982 and 1985.
- BGS has had sight of a database cataloguing discharges from abandoned mines from the Coal Authority, via SEPA. This includes some data on flows and chemistry. There are no records in the Clyde Gateway area but ~2 in Glasgow, and ~15 within ~10 km of the city boundary to the east. This information does not appear to be publically available on SEPA or The Coal Athority websites; BGS will request these data in due course.

Parameter	No. of values – in Clyde Gateway?	No. of values – within ~5km of CG boundary
Core permeability (horizontal)	N	1
Core permeability (vertical)	N	N
Permeability (from field tests?)	~25	~35
Hydraulic conductivity	N	N
Storativity	N	N
Porosity	N	1
Specific capacity	N	3
Transmissivity	N	N
Borehole yield	~5	~25

Table 11 Availability of aquifer properties data for Carboniferous bedrock in Glasgow. Permeability (field test) data are from BGS Engineering Properties database.

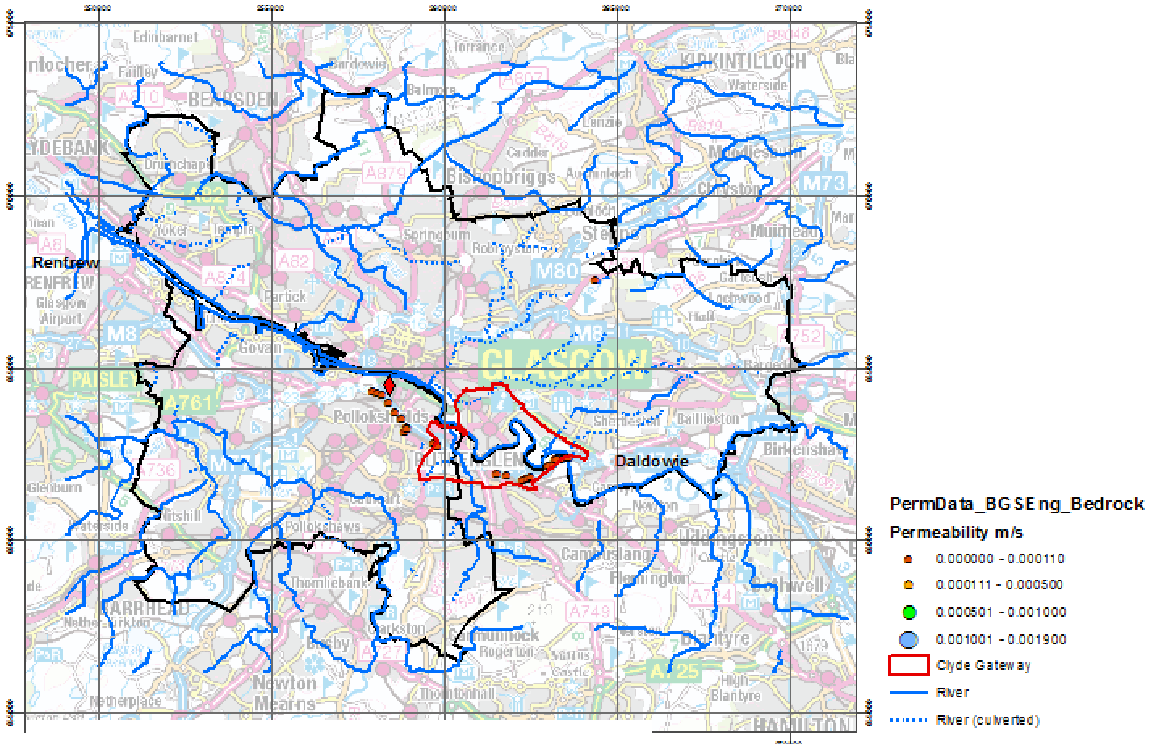


Figure 39 Known permeability measurements for bedrock in Glasgow, from BGS Engineering Properties Database. Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2017. Licence number 100021290 EUL

No. of values – in Clyde Gateway?	No. of values – within ~5km of CG boundary	Notes
~4	~20	All measurements are very old (decades)

Table 12 Availability of groundwater level data for Carboniferous bedrock in Glasgow

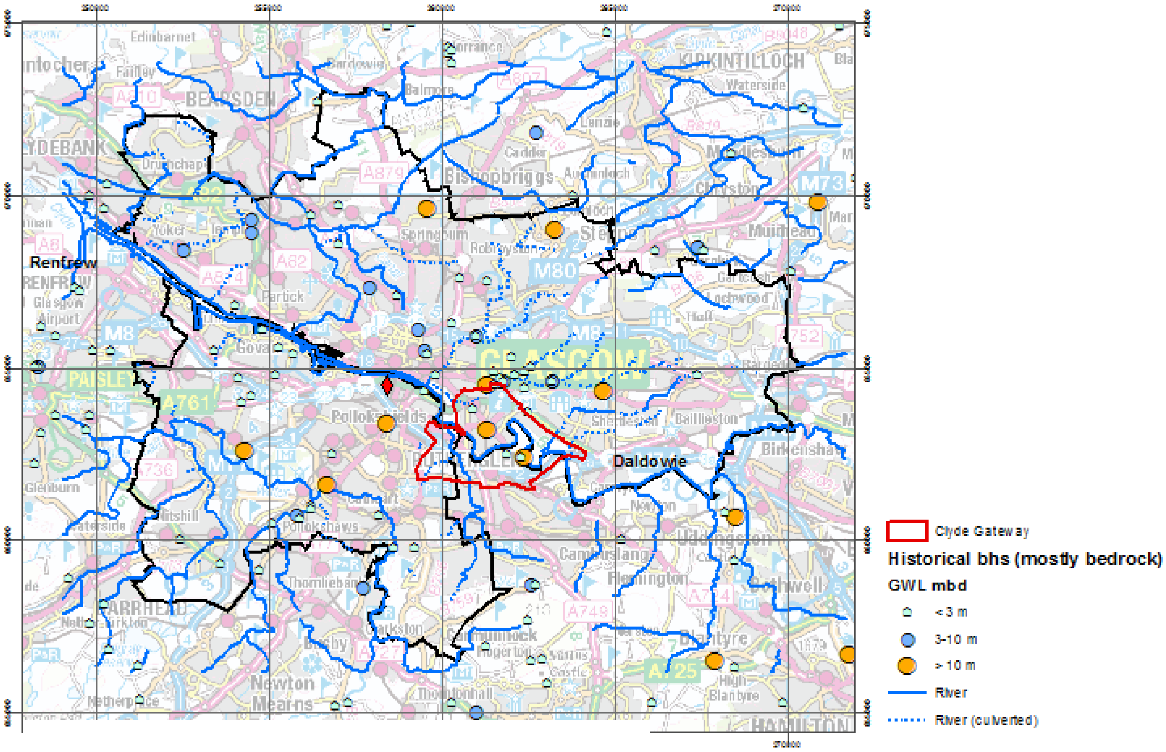


Figure 40 Known groundwater level measurements for bedrock in Glasgow, from various sources GWL mbd = groundwater level, metres below datum (datum is normally approximately ground level). Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2017. Licence number 100021290 EUL

4.3 SUPERFICIAL DEPOSITS HYDROGEOLOGY

Significantly more has been researched and is known about the hydrogeology of superficial deposits than about bedrock in Glasgow and the Clyde Gateway area.

The known hydrogeology and a conceptual model of groundwater in superficial deposits in Glasgow are described in Ó Dochartaigh et al. (in review). A simple numerical model simulating groundwater flow through the superficial deposits in central Glasgow is described in Turner et al. (2015). A brief summary of the known hydrogeology and hydrogeological data is given here.

The Quaternary geological sequence in the central Clyde valley in Glasgow, including the Clyde Gateway area, forms a shallow complex aquifer system with a sequence of hydrogeologically heterogeneous lithostratigraphic units. Three Quaternary lithostratigraphic units – the Bridgeton Sand, Gourock Sand and Paisley Clay members – together form a linear aquifer approximately 2 to 3 km wide and typically between 10 and 30 m thick beneath central Glasgow (Figure 41, Figure 42). This aquifer is highly heterogeneous both naturally, due to varying lithology within aquifer units and to the varying influence of the tidal River Clyde with distance from the river; and due to urban influences, such as altered surface permeability, subsurface flowpaths, and urban recharge (Dochartaigh et al., in review).

The uppermost of the aquifer units, the Gourock Sand Member, and the lowermost Bridgeton Sand Member, are dominated by coarse-grained sediment (gravel and/or sand), and are moderately to locally highly permeable. The Paisley Clay Member usually lies between the Gourock and Bridgeton members, but sometimes overlies the Bridgeton Sand Member with no overlying Gourock Sand Member (Figure 42). It is dominated by fine-grained sediment (silt and/or clay), but contains significant layers and/or lenses of coarser-grained sediment, and as a consequence shows locally moderately high hydraulic conductivity. It appears to allow groundwater flow locally, but at a city scale it has relatively low hydraulic conductivity. All three units are formed largely of marine sediment, although the Gourock Sand Member also includes some alluvium in its uppermost parts. At a city scale, the similarities and differences in hydraulic conductivity between the units are largely controlled by lithological differences, which are in turn controlled by depositional environment and process. However, there are likely to be strong influences on hydraulic conductivity, at scales of <1 to ~10s of metres, resulting from the known local variability in depositional and post-depositional environment (Ó Dochartaigh et al. in review).

A conceptual model of groundwater occurrence and flow within the Quaternary aquifer is described in Section 4.4.

The vulnerability of groundwater at the uppermost water table (i.e. in the Quaternary aquifer) in the Clyde Gateway area is indicated by the national map of groundwater vulnerability (Scotland) (Figure 45). This indicates that groundwater in the uppermost Quaternary aquifer is highly vulnerable across much of the area, with zones of low vulnerability. However, this national-scale map is not likely to provide an accurate assessment of the actual vulnerability of groundwater in the small urban Clyde Gateway area. The widespread presence of anthropogenically altered ground is likely to have a major impact on local groundwater vulnerability that cannot be accurately assessed without detailed local investigations.

Available hydrogeological data for superficial deposits in Glasgow:

- The known availability of superficial deposits aquifer properties data is summarised in Table 13 and Figure 43.
- The known availability of superficial deposits groundwater level data is summarised in Table 14Table 14 and Figure 44.

- There are five known currently active superficial groundwater monitoring boreholes in the Clyde Gateway: all set up by BGS and currently managed by SEPA, and being monitored for groundwater level, temperature, and in one or two cases, SEC. Another ~15 boreholes in Glasgow, within ~5km of the Clyde Gateway, were monitored at some point in the last fifteenyears for groundwater levels, but are not currently being monitored.
- There are a number of chemistry analyses for superficial deposits in Glasgow, all from contaminated land/development sites, and focussed on contaminants. All were collected between 2003 and 2013, and most from 2007 to 2010 in eastern Glasgow. A dataset of 250 water chemistry analyses from 68 boreholes in three Quaternary aquifer units (the Gourock Sand, Bridgeton Sand and Paisley Clay members), and 440 water chemistry analyses from 68 boreholes in artificial ground deposits in Glasgow, has been collated by BGS (Ó Dochartaigh et al., in review). Only a subset of these sample analyses has been assessed as reliable data, and full inorganic chemistry is not available for all of these (Ó Dochartaigh et al., in review RSE). Further details of the groundwater chemistry as assessed from this dataset are provided in Ó Dochartaigh et al. (in review).

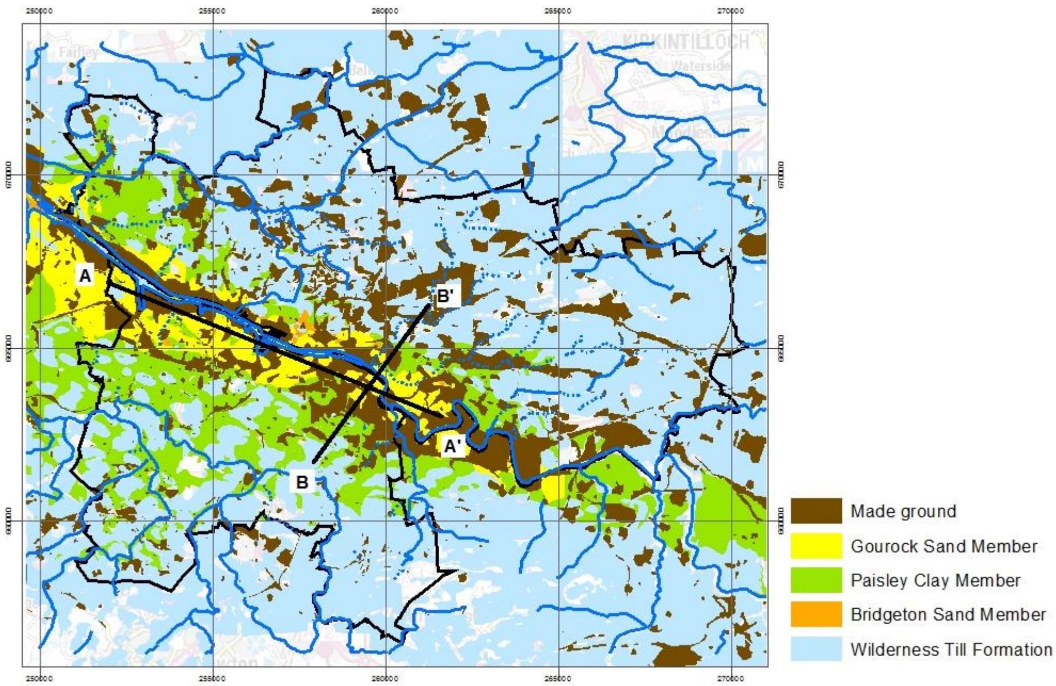


Figure 41 Simplified surface Quaternary geology of Glasgow showing key hydrogeological units and lines of cross-sections in Figure 43. Geology exported from 3D geological model (see Monaghan et al., 2014) (from Ó Dochartaigh et al., in review). Geological Data, BGS Copyright, NERC. Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2017. Licence number 100021290 EUL.

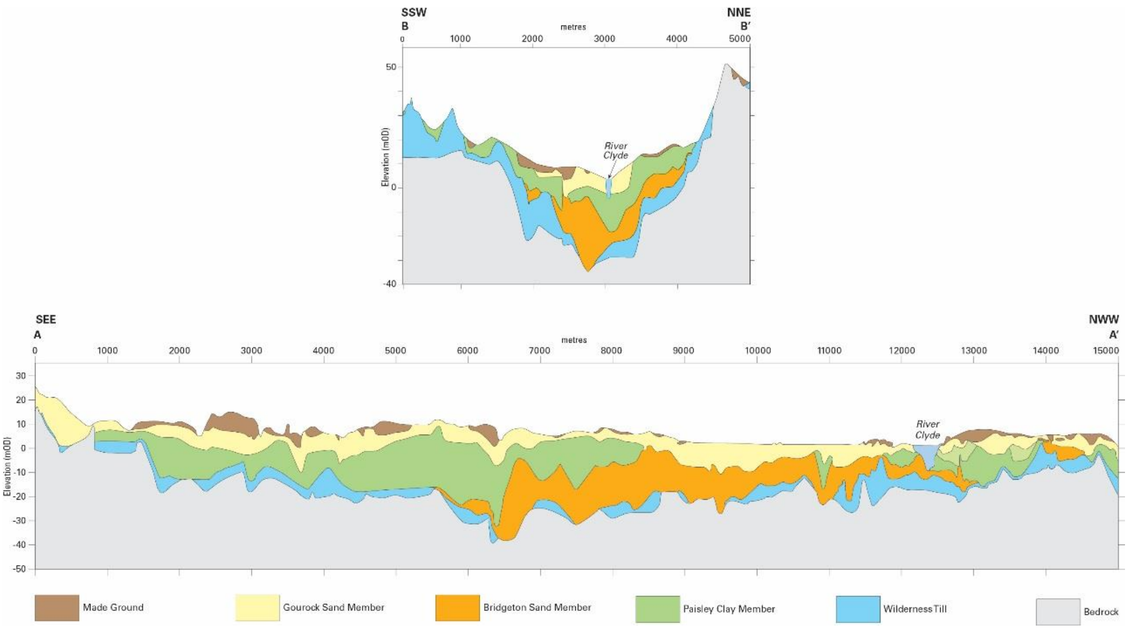


Figure 42 Lithostratigraphic cross-sections along the lines shown in Figure 42, from 3D Quaternary geological model (Monaghan et al., 2014) (from Ó Dochartaigh et al., in review). Note variable vertical and horizontal scales.

Parameter	No. of values – in Clyde Gateway?	No. of values – within ~5km of CG boundary
Permeability (from field tests?)	~25	~10

Table 13 Availability of aquifer properties data for superficial deposits in Glasgow

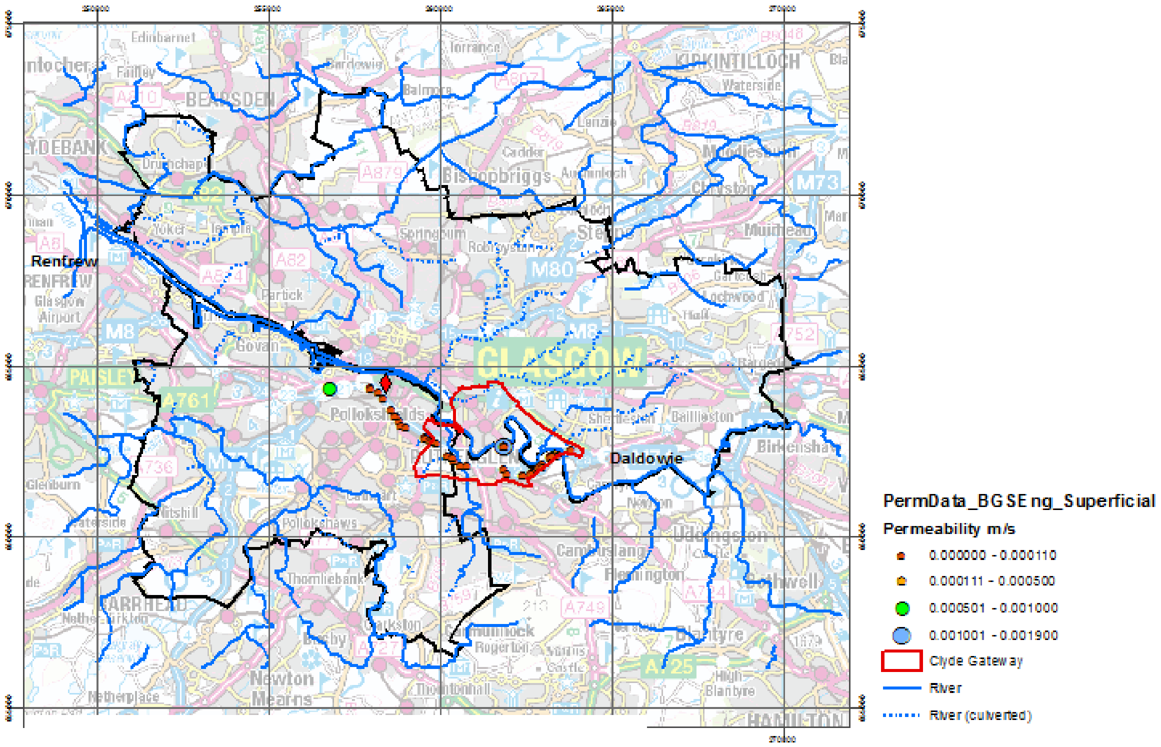


Figure 43 Known permeability measurements for superficial deposits in Glasgow, from BGS Engineering Properties Database given in metres/second (m/s). Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2017. Licence number 100021290 EUL

No. of values – in Clyde Gateway?	No. of values – within ~5km of CG boundary	Notes
~135	~240	Almost all spot measurements

Table 14 Availability of groundwater level data for superficial deposits in Glasgow

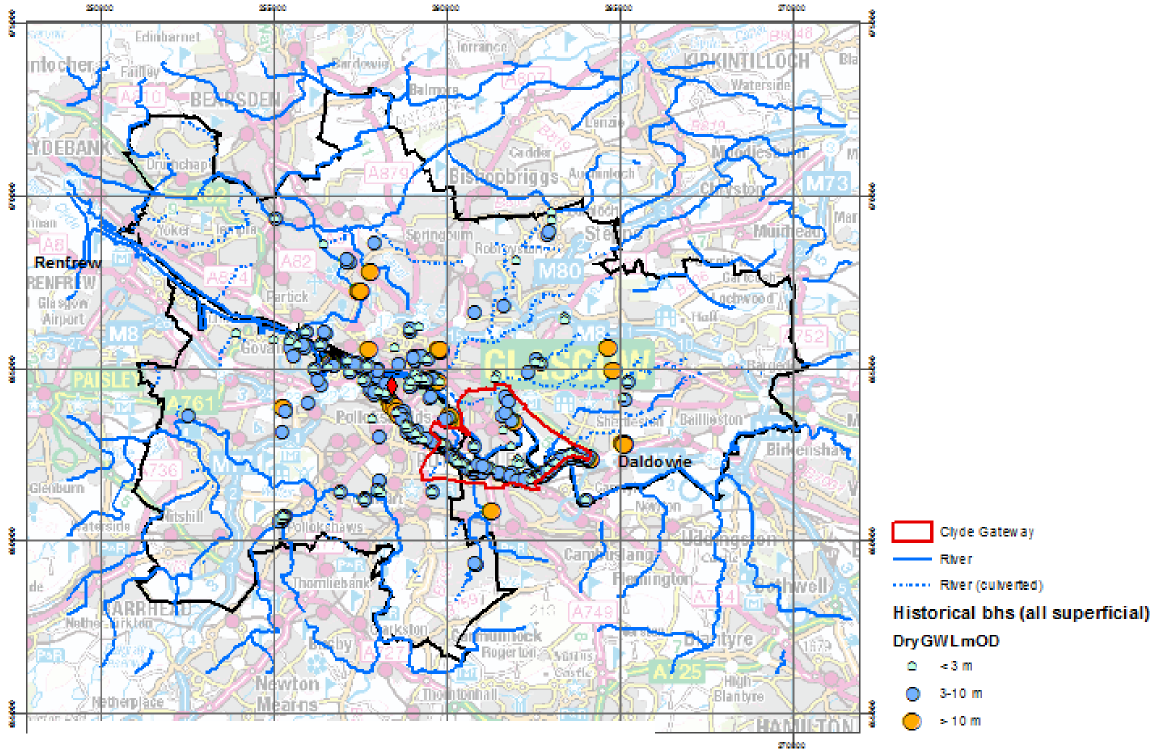


Figure 44 Known groundwater level measurements for superficial deposits aquifers in Glasgow, from various sources. Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2017. Licence number 100021290 EUL

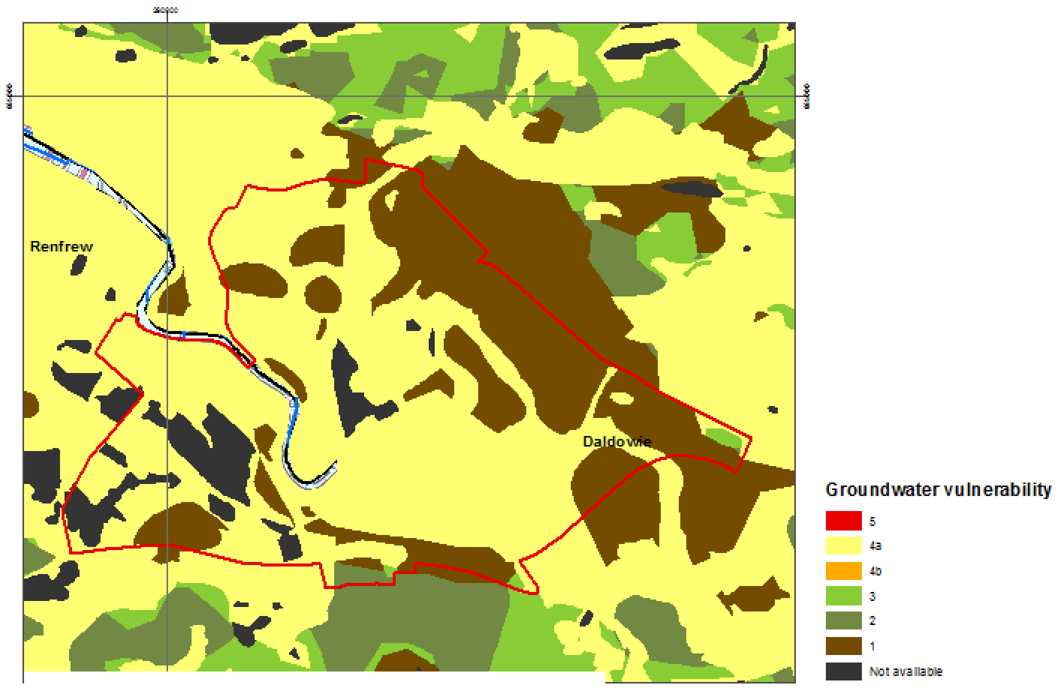


Figure 45 Groundwater vulnerability (at the uppermost water table) in the Clyde Gateway. Key: 5 = highest vulnerability; 1 = lowest vulnerability.

4.4 CONCEPTUAL MODEL OF GROUNDWATER SYSTEM IN THE CLYDE GATEWAY AREA

The simple 3D conceptual model of the groundwater system (superficial and bedrock) described below is largely taken from Ó Dochartaigh et al. (in review). It is based on the available data and information, which are reviewed above. Far more is known of the groundwater system in the Quaternary aquifer. The conceptual model includes an assessment of geological structure, aquifer properties, groundwater levels and chemistry, and groundwater flow paths. It forms the basis for identifying potential pollutant pathways and receptors, and will help to determine the optimum design for groundwater monitoring activities, and in interpreting acquired monitoring data.

4.4.1 Quaternary aquifer

A simple conceptual model of the groundwater system in the Quaternary aquifer in central Glasgow, including the Clyde Gateway area, is shown in Figure 47 (from Ó Dochartaigh et al., in review).

The Gourock Sand and Bridgeton Sand members appear to form a single hydraulically connected aquifer unit where the former directly overlies the latter. The Paisley Clay Member is also hydraulically active, although it has lower permeability overall than the other two aquifer units, and where it occurs between the two other aquifer units, groundwater in all three is likely to be hydraulically connected (Figure 46).

Other Quaternary geological units in Glasgow are likely to be less significant hydrogeologically, because they are typically thinner, laterally restricted and/or have relatively low permeability. Where minor permeable (gravel and sand-dominated) units occur they may allow local groundwater storage and flow, and where they directly over- or under-lie one of the main three aquifer units they may contribute to overall groundwater storage and flow in the main aquifer, but they are not likely to be significant at a city scale.

The Quaternary aquifer is overlain by widespread, highly heterogeneous anthropogenic deposits, and the surface land cover is heavily urbanised. The generally high permeability and widely unconfined nature of the upper parts of the aquifer mean that it is likely to accept potential recharge reaching its upper surface. Preliminary modelling estimated average long term recharge from rainfall to the aquifer at 275 mm/year (Turner et al., 2015). This model took into account some urban processes, specifically runoff from paved surfaces, and sewer leakages, but did not take all urban processes into account. Groundwater is likely to recharge to the Quaternary aquifer from a number of sources as well as directly from rainfall: by groundwater inflow from the upstream Quaternary aquifer; from lateral shallow groundwater flow from adjacent Quaternary units, including the Wilderness Till Formation; from leakage from mains water pipes; and potentially by upward flowing groundwater from the underlying Carboniferous bedrock.

At the city scale, groundwater level elevations show that overall groundwater flow directions through the Quaternary aquifer are down-valley, from south-east to north-west. There is also evidence from groundwater-river level relationships of a component of flow convergent towards the River Clyde from the edge of the aquifer. This is likely to include groundwater discharge to the Clyde. Local reversal of this convergent flow in one area in centre-west Glasgow has also been observed, driven by a groundwater level gradient from the river into the aquifer for at least 50 m distance away from the river. On a very local scale, extensive buried infrastructure (e.g. building and quay walls, engineered river banks) is also likely to influence groundwater flow (Ó Dochartaigh et al., in review).

Two mechanisms drive the strong observed relationship between groundwater level response, and rainfall and river stage fluctuations. Rapid groundwater level change – on a scale of hours – is driven primarily by pressure changes in the aquifer as it responds to rising and falling piezometric head in the River Clyde. Slower, longer lasting groundwater level changes – on a scale of days to weeks – occur in response to the physical flow of water through the aquifer, from the infiltration of rainfall at the ground surface and/or the infiltration of river water through the river bed. The rapid, pressure head driven connection between River Clyde stage and Quaternary groundwater levels is clearly demonstrated by tidal forcing of groundwater levels. This effect is evident throughout the tidal zone of the River Clyde in Glasgow, in all the monitored aquifer units, and at distances of up to 200 m from the river, although the greatest effects are seen closest to the river. A small tidal influence on groundwater levels is also seen some 3 km (straightline distance) upstream of the navigational tidal limit of the River Clyde, indicating that tidal impacts on groundwater extend further upstream than this nominal limit (Ó Dochartaigh et al. in review).

Consistently more mineralised groundwaters are seen in Glasgow than in non-urban areas, with higher concentrations of most major and trace ions, suggest widespread urban and/or industrial contamination. Significant increases in groundwater conductivity over relatively short timescales, as seen in one monitoring borehole, indicate that there is active flow of contaminated groundwater through some parts of the aquifer. Widespread elevated concentrations of major ions such as Ca, K and SO_4 are likely to be linked to contamination from urban waste material, such as cement, metals, mine spoil or chemicals from activities such as building, manufacturing, mining and industrial processes such as chromite ore processing. The elevation of Cl and Na concentrations across the study area, not just close to the tidal section of the river, is also likely to be linked to pollution, particularly as there is not a strong correlation, even in natural Quaternary deposits, between Na and Cl. However, the relatively low NO_3 values in urban groundwater indicate that sewage contamination of groundwater is not significant or widespread. The highly elevated concentrations of trace metals, including As, Cr and Pb, in specific areas of the city, in particular an area in east Glasgow, indicates that historical industrial contamination at specific sites, from activities including mining, chromite ore processing and the manufacture of iron and steel, is still impacting on the quality of groundwater in the Quaternary aquifer system (Ó Dochartaigh et al., in review).

The spatial distribution of groundwater chemistry provides no evidence of evolution of groundwater chemistry down-valley within Glasgow. The effects of contamination on groundwater chemistry are likely to be far stronger than any evolutionary changes with groundwater flow. There is, however, strong evidence for specific areas of greater contaminant impact, related to historical industrial activity, such as elevated chromium and lead at particular sites (Ó Dochartaigh et al., in review).

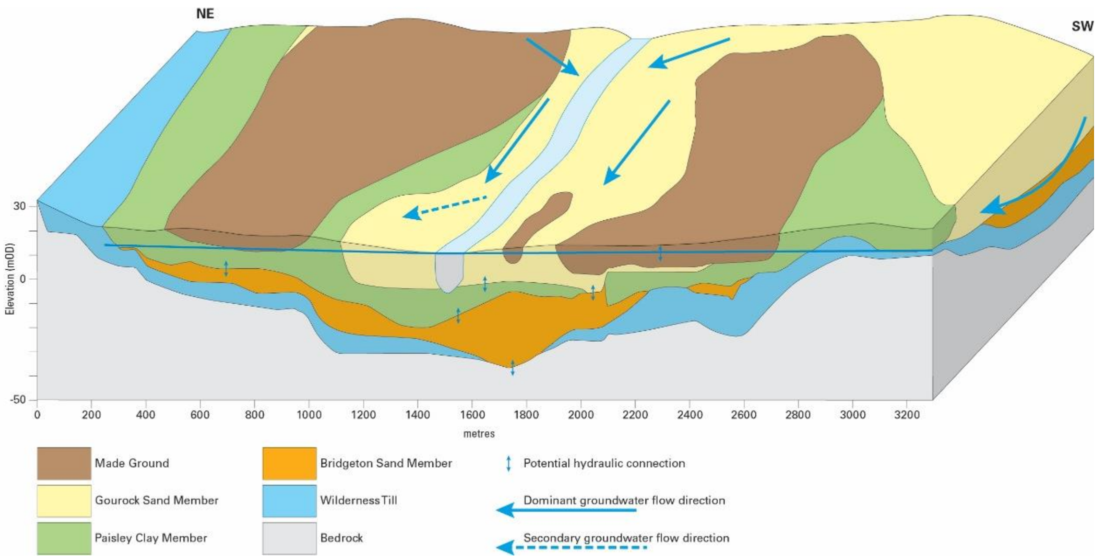


Figure 46 Conceptual model of groundwater occurrence and flow in the Quaternary aquifer in Glasgow, indicating groundwater flow directions; hydraulic connections between aquifer units and river; and groundwater level in the Gourock and Bridgeton Sand members from Ó Dochartaigh et al., in review.[Geological Data, BGS©NERC]

4.4.2 Carboniferous aquifer

No numerical modelling of groundwater in bedrock aquifers in Glasgow has been undertaken by BGS or as documented in published literature. The limited available information suggests that the hydrogeology of the Carboniferous sedimentary aquifers is complex. The aquifers are likely to be moderately productive, to contain significant amounts of groundwater, and to be dominated by fracture flow, and it is likely that groundwater flow paths are relatively deep and long. Hall et al. (1998) concluded that Glasgow is the focal point for much of the groundwater discharge from the Central Coalfield, with prevailing groundwater flow from the east, north-east and south-east. However, this hypothesis was not well constrained by hydrogeological data, because of the lack of groundwater level measurements for groundwater in the Carboniferous aquifers in the Glasgow area. The limited available data on groundwater chemistry in the Carboniferous indicates that groundwater is often naturally moderately to highly mineralised, with abundant iron and manganese in solution (Hall et al., 1998; Robins, 1986; Ball, 1999). Extensive mining and post-mining measures in Glasgow are likely to have led to significant changes in the natural groundwater regime, increasing the complexity of groundwater flow and possibly reducing natural groundwater quality. Mine dewatering declined over the 20th century and ended in the 1980s (Ó Dochartaigh, 2005), and it is probable that groundwater levels rose over and after this period, but there is no modern monitoring of groundwater levels in the bedrock. Anecdotally, rising groundwater levels, poor groundwater quality, and other mining-related issues are not a problem in Glasgow (Ó Dochartaigh, 2005).

The likely active flow of groundwater in the Carboniferous bedrock aquifer means there is likely to be hydraulic connection between it and the overlying Quaternary aquifer system. However, there are no observed data to characterise or quantify any such connection.

5 Geothermal data for the Glasgow area

Geothermal energy is the heat that is generated and stored within the Earth. If it can be extracted, this heat can be used as an energy source. Heat flow is the standard means of gauging the size of the heat resource beneath any given point at the Earth's surface. This is the measure of the amount of heat travelling through Earth's crust, generally expressed in milliwatts per metre square (mW m^{-2}). Heat flow can be calculated using borehole measurements of the geothermal gradient (the rate at which temperature increases with depth) and the thermal conductivity of the rock (e.g. see Gillespie et al., 2013). Thermal conductivity can be more difficult to measure than temperature, particularly in heterolithic strata, and is therefore not always available in conjunction with temperature measurements. Temperature data measured in boreholes provide the best currently available alternative to heat flow measurements as a means of examining the size and distribution of the heat resource beneath Scotland (Gillespie et al., 2013). Heat flow, thermal conductivity and temperatures are considered as thermal data. Thermal data for Glasgow and the Clyde Gateway are summarised below and discussed in terms of minewater geothermal and Hot Sedimentary Aquifer (HSA) geothermal.

5.1 HEAT FLOW

The most recent heat flow map for the UK is shown in Figure 47, from Busby (2011). This heat flow map originates from the third version of the Geothermal Catalogue of the UK (Rollin, 1987) and includes data from 390 deep (> 1000m) boreholes.

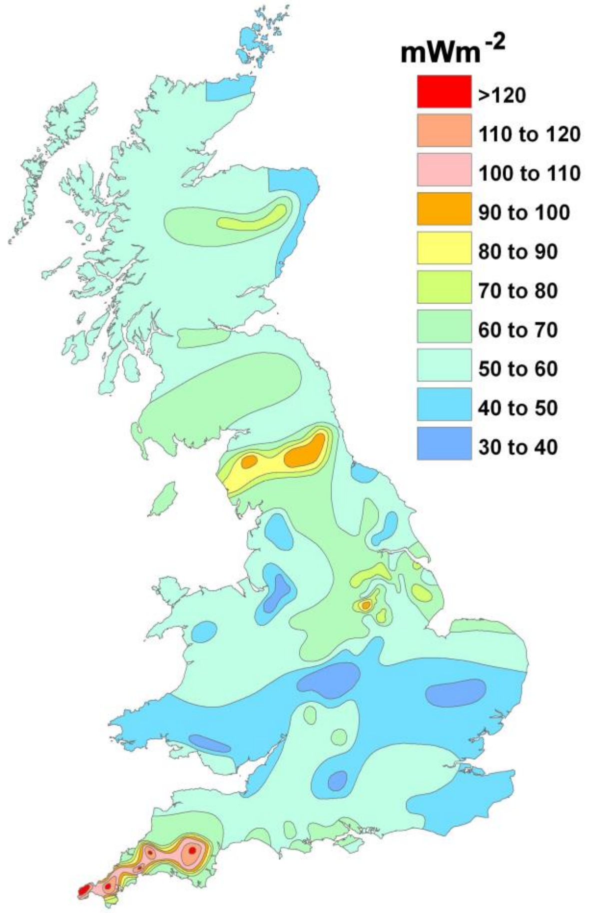


Figure 47 Heat flow map for the UK ([1]version from Busby (2011)).

Scotland sits on a geologically stable part of Earth's crust and there is no indication of the presence of a substantial heat resource in accessible parts of the subsurface (Gillespie et al., 2013). However, it is thought that the size of the heat resource may have been underestimated due to the impacts of palaeoclimate, as discussed below (e.g. Westaway and Younger, 2013; Busby et al., 2015).

The heat flow dataset for Scotland is relatively small, and no new values have been reported since the 1980s (Gillespie et al., 2013). In the most recent report on the potential for deep geothermal energy in Scotland, Gillespie et al. (2013) compiled heat flow values from 35 onshore boreholes in Scotland (listed in their Table 3). Thirty-four of these data are collated in the second version of the Catalogue of Geothermal Data for the UK (Burley et al., 1984). Data for the Glenrothes borehole came from Brereton et al. (1988).

Most of the reported heat flow values in Scotland derive from measurements in boreholes < 400 metres deep (Gillespie et al., 2013). Because geothermal temperatures from a depth of less than c.2 km depth, were impacted by cooler surface temperatures in previous glaciations in comparison to today's surface temperatures, temperature measurements from shallow depths in the UK generally underestimate the geothermal gradient (e.g. Westaway and Younger, 2013, discussed below). In addition, since thermal conductivity measurements are representative of the rock between the location of temperature measurements in a particular

[1] Note a new version uplifted for climatic effects was published by Busby & Terrington 2017 DOI 10.1186/s40517-017-0066-z

borehole, the greater this distance is, the greater the thickness of the crust being accounted for. Therefore, heat flow calculated from temperature measurements at greater depths are often considered to be more reliable (Gillespie et al., 2013). The following comments are summarised from Gillespie et al. (2013) and reflect the degree to which heat flow measurements in Scotland can be considered accurately to reflect the size of the heat resource at depth:

- Nine values are from lake sediments in Loch Ness; published values include significant corrections so their reliability, and the degree to which they can be compared meaningfully with values measured in solid rock, are not clear and they should therefore be treated with caution. In addition, Loch Ness overlies the Great Glen fault which may act to focus or disperse heat locally and may therefore not be a good indicator of background regional heat flow.
- Four values come from radiogenic granite in the East Grampians region and will be influenced by local heat production, so might not be representative of background heat flow.
- Fifteen values are from boreholes in sedimentary rocks of Carboniferous/Devonian age. The temperature of these rocks may have been affected by large-scale convective transfer of heat in groundwater.
- The remaining seven measurements are from metamorphic rocks, and although these rocks have low permeability there is a growing body of evidence that suggests crystalline rocks may be affected to some degree by convective heat transfer. A value of 29 mW m^{-2} from Tilleydesk (Ellon) was included in the Burley et al. (1984) data but was not formally reported by the group that measured it (Oxford University Heat Flow group), presumably because it is a suspect value.
- In all parts of Scotland, the geothermal gradient in the near-surface is likely to be perturbed by climate warming since the last glaciation. This is discussed below.

In a subsequent version of the Geothermal Catalogue (Rollin 1987) there are two additional heat flow measurements for Scotland (in Selkirk and Edinburgh), not included in previous analysis.

The heat flow values for Scotland presented in Gillespie et al. (2013) range from 29 to 82 mW m^{-2}; with a mean of 56 mW m^{-2} and median of 57 mW m^{-2}. If the potentially anomalous Tilleydesk (Ellon) value is removed then the mean value for Scotland increases to 57 mW m^{-2} and the minimum value is 37 mW m^{-2} (Gillespie et al., 2013).

5.1.1 Glasgow area

There are no available heat flow measurements in the Clyde Gateway area; therefore data have been considered within 20 km of the boundaries of the Clyde Gateway area (Glasgow area). There are four heat flow and thermal conductivity measurements for the Glasgow area (Figure 48**Error! Reference source not found.** and Table 15); all are within the north and west of the city. In comparison to data used for the heat flow map of the UK (Figure 47) these measurements are all from boreholes that are relatively shallow (Table 15).

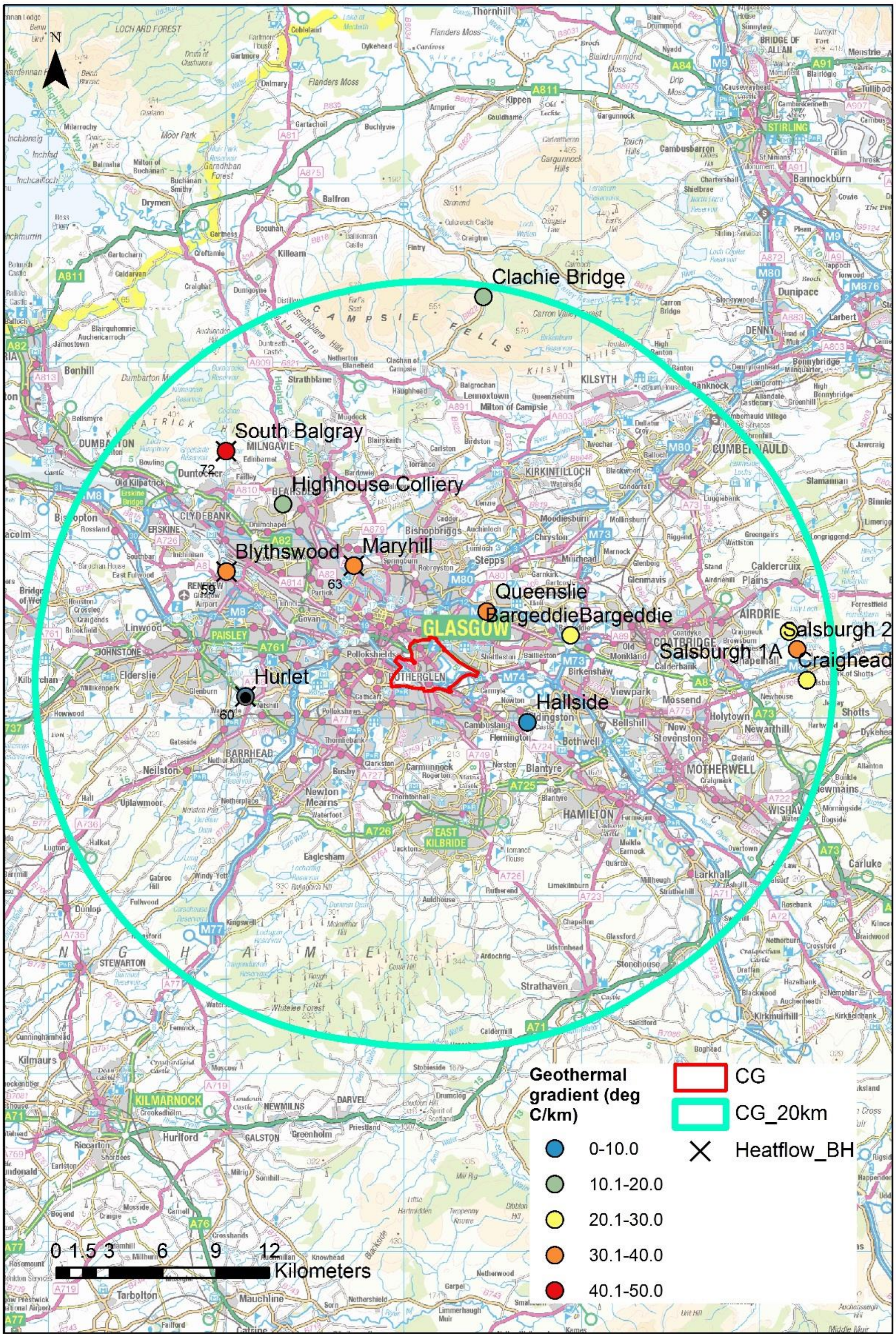


Figure 48 Locations of measured geothermal gradient and heat flow around Glasgow. Temperature data are from Burley et al. (1984) in Gillespie et al. (2013) and additional temperature data are from Rollin (1987) and heat flow boreholes from Burley et al.

(1984) (Heatflow_BH). CG is the Clyde Gateway area, CG_20 km is the 20 km buffer zone around CG. There is no geothermal gradient or temperature given for Hurlet (black dot). Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2017. Licence number 100021290 EUL.

BH Location	**Grid Reference**	**Heat Flow (mW m^{-2}) (Burley et al., 1984)**	**Heat Flow (mW m^{-2}) (Rollin 1987 and Downing and Gray 1986)**	**Heat Flow (mW m^{-2}) (Gillespie et al., 2013)**	**Depth (m bgl)**	**Thermal conductivity (W m^{-1} K^{-1}) (arithmetic mean for the BH)**	**Data quality category**
South Balgray	NS 5000 7500	64/72	64	72	0-137	1.54	C
Blythswood	NS 5003 6823	52/59	52	59	18-106	1.61	C
Maryhill	NS 5718 6856	63	63	63	100-303	2.4	A
Hurlet	NS 5010 6120	60	60	60	95-295	3.92	A

Table 15 Heat flow measurements in the 20 km zone around the Clyde Gateway area. Note there is no temperature information for the Hurlet borehole.

The method for characterising data quality categories (Table 15) as outlined by Burley et al. (1984) is as follows: Category A is "an estimate based on temperatures that are measured in conditions of thermal equilibrium using resistance thermometers in boreholes with no evidence of groundwater flow. There are enough temperature measurements to give a good representation of the temperature profile of the zone for which the heat flow is calculated, and they are to a depth of at least 200 m below the surface…Conductivities are measured from cores, or chippings where the rock is uniform and impermeable, at intervals to give a good representation of the lithologies in the zone for which the heat flow is calculated." For Category C "neither of the sets of conditions in A apply, but the measurements are to a depth of at least 100 metres, and there is no evidence of groundwater flow in the zone for which the heat flow is calculated." Browne et al. (1985) state that the equilibrium temperatures obtained during heat flow determinations are the most reliable and accurate values, but are relatively rare in the Midland Valley. Drill stem tests and virgin stratum temperatures are expected to provide reasonably reliable values, because both measure the undisturbed temperature of fluids in the formation. Minewater temperatures have been omitted from their analysis because they are not measured in a rigorous way. Bottom hole temperatures are of variable quality – in some cases they consist of a series of readings at considerable times after the circulation of drilling rod has stopped, in which case an equilibrium temperature may be established by empirical means (as described in Burley et al., 1984). However, in many cases this correction is not suitable, because insufficient time has elapsed since circulation was stopped. In addition, many values indicated gradients which were anomalously high or low for the particular area and such values have been used with circumspection. The most reliable heat flow measurements were made in the 300 m deep borehole at Maryhill, Glasgow, where

99 temperatures were recorded below 100 m depth, and 82 conductivity values were recorded (Brown et al., 1987).

The distribution of thermal conductivity with depth in the sedimentary crust is one of the major uncertainties in temperature predictions to depths > 2 km (Rollin, 1987). There are 23 borehole measurements of rock thermal conductivity in Rollin (1987) for Scotland. Table 1 and 2 in Gillespie et al. (2013) show values reported for common rock types (reported in Lee et al. 1984 and Wheildon et al. 1984) and for seven broad categories of bedrock in Scotland, respectively. Mean thermal conductivities are also provided for specific lithologies by Rollin (1987) in Table 3. Browne et al. (1985) describe how the variation in conductivity for each lithology in the Upper Palaeozoic in the Midland Valley is considerable and, in addition, the proportion of rock-types in any formation is very variable. The "assumed values have been arrived at in a subjective manner, so that it is difficult to assess appropriate errors on these". The values and standard deviations are: Coal Measures 1.91±0. 25 W m^{-1} °C^{-1}, Passage Group 2.91±0.15 W m^{-1} °C^{-1}, and Lower Carboniferous 2.12±0.25 W m^{-1} °C^{-1} (Browne et al., 1985).

Figure 47 shows that heat flow appears to be slightly higher in the central part of the Midland Valley, than in the surrounding area where a 60 mW m^{-2} contour encloses a cluster of values, some of which are in Glasgow (Gillespie et al., 2013). Browne et al. (1987) suggest that heat flow is possibly slightly higher in the west than in the east of the Midland Valley. Mean heat flow for Glasgow, using the lower and higher values provided respectivel for South Balgray and Blythswood (Table 15), would be 59.7 and 63.5 mW m^{-2} with a standard deviation of 5.4 and 5.9 mW m^{-2}. The difference between these heat flow estimates, provided in Burley et al. (1984), result from differences in estimates of conductivity used in the heat flow calculations. One value is from Benfield (1939), who used thermal conductivities of core samples from the Boreland Borehole (Edinburgh, GR NT 3304, 6942) measured using the "divided bar equipment" . The other value is from Anderson (1940), who used estimates of thermal conductivity from core samples from the Boreland Borehole measured by "Bullard", also using the "divided bar equipment", in conjunction with data from British Association Reports (1880 and 1882). Rollin (1987) and Wheildon and Rollin (1986) chose to use the lower of the two values of heat flow, whereas Browne et al. (1985) and Gillespie et al. (2013) used the higher values of heat flow for these boreholes (Table 15). The only justification for this is in Browne et al. (1985) where these values are stated as "*most reliable determination" in Table 1. However, since the data quality is only rated as C, and the thermal conductivity was not measured in the same borehole, the heat flow at Maryhill and Hurlet should be considered as more reliable estimates. This would suggest a heat flow of 61.5 mW m^{-2} for the Glasgow area. This value is slightly higher than the background heat flow for Scotland, 56 and 57 mW m^{-2}.

A number of reports and papers in the mid-1980s proposed a model to explain the assumed heat flow anomaly in the Midland Valley through regional upflow of groundwater (Browne et al., 1987; Lee et al., 1987; Robins, 1988). Downward flow is thought to predominate in areas of recharge along the southern and northern margins of the Midland Valley where higher elevation provides a higher fluid potential (Robins, 1988). While this model is consistent with topography and the configuration of aquifer units, Browne et al. (1987) state that the supporting evidence is inconclusive, and deep groundwater circulation is likely to be moderate in volume and limited to isolated discrete pathways. Robins (1988) argues that hydrochemical and isotopic data to support this theory are sparse because upwelling deep waters tend to mix with shallow near-surface waters. Other possible reasons for higher heat flows include; thinner crust, more radioactive granitic rocks within the crust, or continued heat flow from Cenozoic igneous activity (Browne et al., 1987) .

It is known that past climate change has affected the temperature at the Earth's surface and therefore the temperature distribution at depth (Westaway and Younger, 2013 and Busby et al., 2015). Each change in surface temperature will propagate into the ground, but the amplitude of the change will decrease exponentially with depth and there will be a time lag with perturbations at surface and at depth (Busby et al., 2015). With depth, this climatic impact on temperature will decrease As such, the geothermal gradient measured in a shallow borehole would indicate a lower heat flow than exists. Westaway and Younger (2013) proposed that the heat flow measurements presented for the UK in Downing and Gray (1986), the geothermal catalogue and Busby (2011) have therefore been systematically underestimated. Busby et al. (2015) showed that when palaeoclimate corrections are applied to heat flow values in the East Grampians region of Scotland, there is an increase in heat flow of 25 %. This effect is particularly acute when calculating heat flow in shallow boreholes (e.g. Westaway and Younger, 2013) such as those listed in Table 15. For Scotland, Westaway and Younger (2013) estimated there may be an additional 18.0 mW m^{-2} heat flux in a very shallow borehole with rocks with thermal conductivity of 3 Wm^{-1} $^{o}C^{-1}$. For a 1 km deep borehole the correction would reduce to 13.5 mW m^{-2} if the heat flow had been calculated as the average for the whole depth of the borehole, or 8.8 mW m^{-2} if it had been calculated from temperature measurements over a limited range of depths at the bottom of the borehole (where there is a smaller impact of paleoclimates). For a 1.5 km deep borehole the corrections would be 9.1 mW m^{-2} and 0.2 mW m^{-2} respectively (Westaway and Younger, 2013).

5.2 TEMPERATURE

The geothermal gradient, and hence temperature at a given depth, depends on the heat flow, thermal conductivity of the rock and groundwater flow (convection). Available temperature data measured in onshore boreholes were collated and reported in the Geothermal Catalogue for the UK. Version two (Burley et al., 1984) is commonly quoted since it is cited in "Geothermal Energy; The potential in the United Kingdom" (Downing and Gray, 1986). However, there are additional data in Version 3 (Rollin et al., 1987). More recently data have become available from Hard Copy temperature logs in the BGS archive, and the BGS National Petrophysical Data Archive. These, and additional data sources for temperature, are discussed in the following section.

The BGS Catalogue of Geothermal Data for the UK (Burley et al., 1984) collated available borehole temperature data as part of the 1977 to 1984 Geothermal Energy Programme of the British Geological Survey, supported by the UK Department of Energy and Commission of European Communities (C.E.C.). The catalogue includes a list of borehole temperature data for 61 boreholes in onshore parts of Scotland; these include many of the boreholes from which heat flow values have been calculated. In most cases, the temperature measurement has been made at, or near to, the bottom of the borehole. Whereas most of the available heat flow data come from depths of less than 400 m below ground surface, the onshore borehole temperature data extend to a depth of around 1,300 m. Boreholes are clustered mainly in Caithness, the East Grampians region, and in the Midland Valley. Temperature data for onshore boreholes in Scotland from Burley et al. (1984) are summarised in Gillespie et al. (2013; Table 4). 17 additional borehole temperature-depth measurements located on the Ordnance Survey NS sheet (west Midland Valley) were included in Rollin (1987), the third revision of the geothermal catalogue.

Busby et al. (2011) produced new temperature maps for the UK using data from the Geothermal Catalogues for the UK, and new data from the BGS National Petrophysical Data Archive and Hard Copy temperature logs. The National Petrophysical Data Archive captured sub-surface temperature data added to the digital archive since the compilation of the Geothermal Catalogues. Hard Copy petrophysical log data are derived mostly from the hydrocarbon industry, British Coal exploration, or from BGS's own onshore research (Busby et al., 2011). Temperature values were extracted at intervals of 100 m bgl, taking into account any deviations of the well from vertical. Due to issues with logging, the depth interval was bracketed by ± 5m (e.g. from 195 to 205 m below ground level, bgl). Due to time constraints, not all logs could be examined and so an approach based firstly on accessibility and quality of data, and then on maximum depth coverage and geographical location in relation to existing data points, was applied. These data were used to compile maps of temperatures at depths below ground level of 100, 200, 500 and 1000 m. From these data, regional trends and anomalies have been defined and a UK-wide geothermal gradient of 28 °C km^{-1} was calculated for the upper 1 km of the sedimentary crust – slightly above the previously quoted value of 26 °C km^{-1}. The distribution of the measured temperature data is variable. For the 100 and 200 m depth intervals there is reasonable coverage across the Central Belt of Scotland; however for the deeper 500 and 1000 m depth intervals the majority of the data are concentrated in central and southern England.

From the data in Burley et al. (1984), Gillespie et al. (2013) calculated an average temperature gradient for each borehole in Scotland using the surface temperature, the borehole temperature at depth, and the depth at which the latter was measured. The average temperature gradient values for all 61 onshore boreholes in Scotland range from 3.7 to 45 ^{o}C /km; the mean is 22.5 ^{o}C/km, and the median is 21.5 ^{o}C /km. The wide range of average temperature gradient values suggests that the gradient in any one borehole is affected by a range of local factors. However, plotted together as temperature versus depth (T-z) the data display a trend defining a temperature gradient of 30.5 ^{o}C /km which persists throughout the entire depth range intersected by these boreholes (down to c.1500 m). When extrapolated, it was found that the best-fit line through all the data intersects the surface at approximately 4.0 ^{o}C; significantly below the current annual average surface temperature in Scotland (taken to be 9.0 ^{o}C, from the average of all the surface temperature data listed in Burley et al., 1984).

This implies that the top end of the geothermal gradient (the part that is typically measured in shallow boreholes) is not simply a continuation of the deeper trend; the gradient must steepen (i.e. the rate of increase in temperature with depth will appear to be smaller) in the near subsurface (Gillespie et al., 2013).This supports the theory that Holocene warming has had an impact on near-surface temperatures in Scotland (Westaway and Younger, 2013 and Busby et al., 2015). Hence, measurements of the geothermal gradient made in individual shallow boreholes are likely to underestimate the geothermal gradient at depth. Browne et al. (1985, 1987) reported that the average temperature gradient (based on borehole temperature versus depth [T-z] data) for boreholes in the Midland Valley was 22.5 °C/km. This is significantly lower than the value suggested by Gillespie et al. (2013) for onshore boreholes in Scotland using the same dataset. The difference is because the data have been interpreted in different ways: Browne et al. (1987) 'pinned' the top of their interpreted geothermal gradient to a surface temperature of 10 °C (representing the present day surface temperature at Grangemouth), whereas Gillespie et al. (2013) used only temperatures measured at or near the base of boreholes to calculate an 'averaged geothermal gradient'.

When considering both onshore and offshore boreholes (n=133), ranging up to 5 km in depth, Gillespie et al. (2013) found the geothermal gradient to be slightly curved, with an increase at depth, from 30.5 °C/km in the shallowest third, to 46.7 °C/km in the deepest third. These values equate to temperatures of 100 °C and 150 °C at depths of approximately 3.0 and 4.0 km, respectively. However, the data defining the trend come mainly from offshore boreholes and caution should be taken when extrapolating the same gradient onshore. Gillespie et al. (2013) suggested that this increase in temperature gradient with depth could result from the impacts of palaeoclimate, or from the proximity of some offshore areas to the continental margin where the crust might be thinner and heat flow therefore higher. Even if onshore settings do not follow the higher temperature gradient of offshore settings below 1.5 km, the gradient of 30.5 °C/km defined by the data from onshore boreholes suggests temperatures could be around 150 °C at 5 km depth in onshore areas. The gradient for onshore data is defined mainly by boreholes in the Midland Valley, so the level of confidence attached to an extrapolation to 5 km is highest for that area (Gillespie et al.,2013).

5.2.1 Glasgow area

There are 13 temperature measurements within 20 km of the Clyde Gateway area (Table 16); two are from temperature logs, three from equilibrium temperature measurements, four from bottom hole temperatures, three from Drill Stem Tests (DST), and one is from minewater temperature measurements. Most data were extracted from the Geothermal Catalogue Version 2 (Burley et al., 1984), an additional site (Salsburgh 2) was available in Version 3 (Rollin, 1987) and another (Bargeddie 1, with two DSTs) was available in the DECC Onshore Wells Archive accessible to BGS. A number of temperature measurements from the Baseline Geochemical Survey were available but discounted due to the distance between the borehole outlet and sampling point. There were no additional temperature measurements in this area from the National Petrophysical Archive or hard copy logs. However, hard copy logs were not included in the analysis if they appeared to be anomalous because this might represent groundwater flow rather than background geothermal gradients (*C. Gent, pers comm.*).

The average geothermal gradient for the measured depth/temperatures in the Glasgow area is 30.2 ^{o}C/km with an un-pinned surface temperature of 7.3 ^{o}C (Figure 49). However, for individual boreholes, the measured temperature gradient varies between 6 and 38.4 ^{o}C/km. There are no clear spatial patterns in the geothermal gradient measured at individual boreholes (Figure 48). However, due to differences in surface temperatures it is difficult to compare measurements of geothermal gradients made for individual boreholes. The scatter of data in Figure 49 shows that there could be some local variability in the geothermal gradient dueto local effects, such as groundwater flow, lithology or differences in heat flow.

The Highhouse Colliery plots relatively closely to the average geothermal gradient line (Figure 49), indicating that the temperature in the mine might also reflect the geothermal gradient for Glasgow.

Borehole name	Unit	Type	X	Y	Start height (m aOD)	Depth (m bgl)	Temp (°C)	Geothermal gradient (°C/km)	Heat flux (W $m^{-1} K^{-1}$)	Data source
Hallside	Scottish Upper Coal Measures Formation	LOG	266940	659750	54	350	11.8	6	N/A	Burley et al. (1984)
South Balgray	Clyde Plateau Volcanic Formation,	EQM	250000	675000	30	160	15.3	45	72	Burley et al. (1984)
Blythswood	Limestone Coal Formation, Clackmannan Group Type	EQM	250030	668230	2	105	12	37.1	59	Burley et al. (1984)
Queenslie	Coal Measures Group	BHT	264660	665980	78	691	36	38.4	N/A	Burley et al. (1984)
Maryhill	Limestone Coal Formation, Clackmannan Group Type	EQM	257180	668560	55	303	20	34	63	Burley et al. (1984)
Clachie Bridge	Lower Carboniferous, Upper Old Red Sandstone	LOG	264470	683680	271	300	13.2	16	N/A	Burley et al. (1984)
Salsburgh 1A	Carboniferous Limestone	BHT	281660	664860	223	883	30	24.1	N/A	Burley et al. (1984)
Salsburgh 1A	Carboniferous Limestone	DST	281660	664860	223	874	29	23.2	N/A	Burley et al. (1984)
Salsburgh 2		BHT	282110	663850	223?	1104	44	32.1	N/A	Rollin et al. (1987)
Craighead		BHT	282670	662120	263	977	35	27.2	N/A	Burley et al. (1984)
Bargeddie 1		DST1	269378	664649	91	988	40	32	N/A	DECC Onshore Wells
Bargeddie 1		DST2	269378	664649	91	783	30	27.8	N/A	DECC Onshore Wells
Highhouse Colliery	Limestone Coal Formation, Clackmannan Group Type	MWT	253210	672020	75	436	18	19.5	N/A	Burley et al. (1984)

Table 16 Boreholes with temperature measurements within 20 km of the Clyde Gateway area. LOG is log temperature, EQM is equilibrium measurement, MWT is minewater temperature. For Bargeddie 1, no surface temperature was provided; therefore the interception temperature from the average geothermal gradient was used (Figure 49).

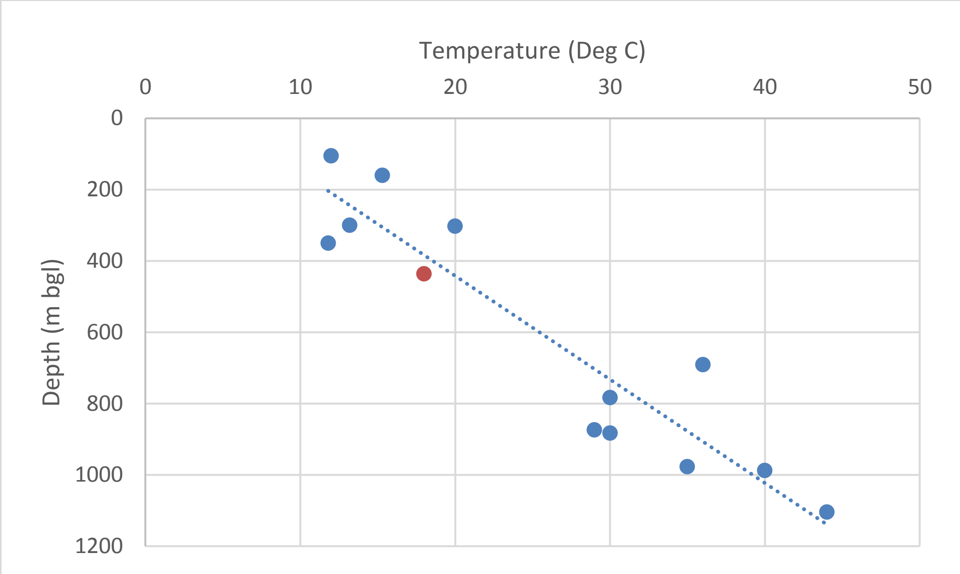


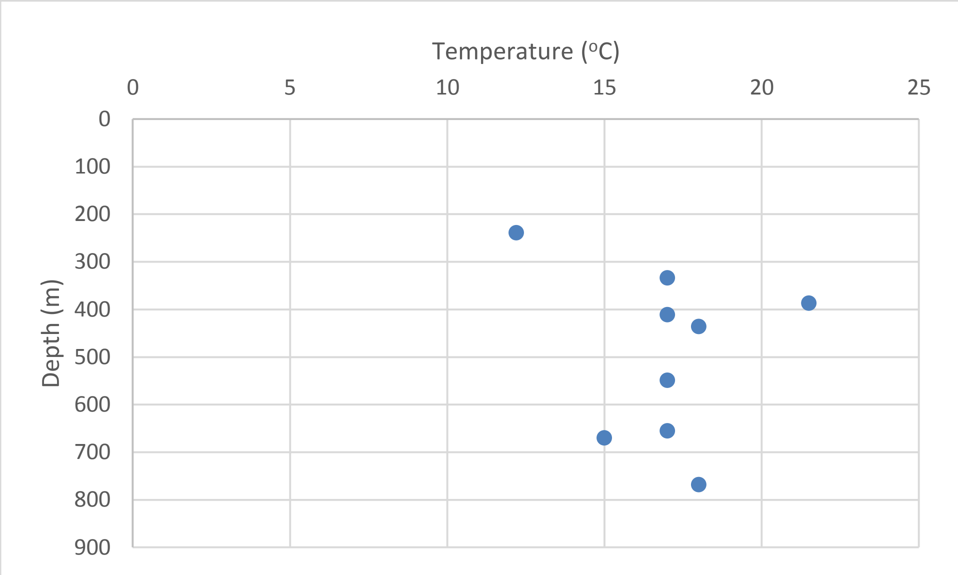
Figure 49 Measured temperature and depth within 20 km of the Clyde Gateway area; 10 data points from Burley et al. (1984), one from Rollin et al. (1987), two from the DECC Onshore Well archive. The red data point is temperature measured in the Highhouse Colliery. The geothermal gradient is 30.2 ^{o}C/km with a surface temperature of 7.3 ^{o}C.

5.3 MINE WATER

Abandoned mines can provide access to thermal reservoirs from which to extract heat. Glasgow is underlain in many parts by a network of abandoned mines from which coal, ironstone and other minerals were extracted. An open-loop Ground Source Heat Pump (GSHP) installation utilising mine water at Shettleston, in east Glasgow, c. 1.5 km to the north-west of Clyde Gateway, has been operating since the year 2000. It is a small scheme, serving 16 dwellings over an area of 1600 m^2, using water from 100 m depth and 12 ^{o}C, pumped at 5 to 10 l/s (Figure 50). The water is returned at 3 ^{o}C (Banks et al., 2004).

Similar to other mining areas, the underground mine workings at Clyde Gateway exist over a range of depths, meaning that the temperature could vary quite significantly between the uppermost and lowermost levels due to the geothermal gradient. Mines that extend to relatively deep levels, can provide relatively easy access (e.g. via remnant shafts) to higher temperature water. The shallower mine levels can be utilised for re-injection of cooled water. A relatively large system of abstraction and injection (and heat storage) at different depths within mines is used for a district heat system for municipal and some private buildings in the town of Heerlen, in the Netherlands (see Verhoeven et al., 2014).

Minewater temperatures for nine boreholes in the Midland Valley have a fairly narrow temperature range – from 12 to 21 °C, with a mean (and median) of 17 °C (Gillespie et al.,



2013).

Figure 500 shows that there is little correlation between temperature and depth. Preferential fluid flow pathways can form through mine tunnels and shafts; thus in some places mine water might not be in thermal equilibrium with the geothermal gradient. However, there are few data points and a limited depth of measurement (between 200 and 800 m bgl). It is also not simple to predict the temperature of water pumped from a borehole, as water of different temperatures may be entering the borehole at different depths (Gillespie et al., 2013).

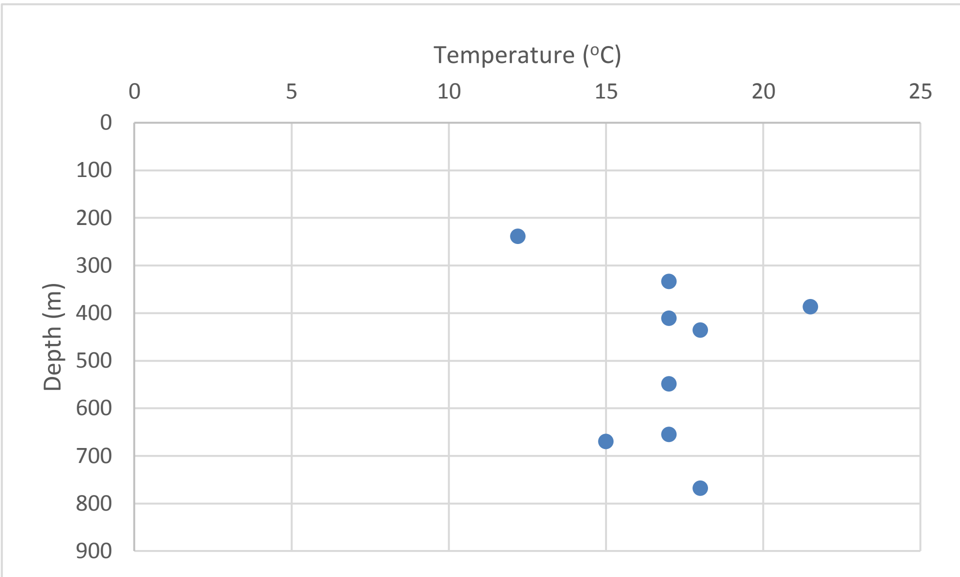


Figure 50 Measured water temperature with depth from mines in the Midland Valley of Scotland (Burley et al., 1984).

Ó Dochartaigh (2009) described temperature data collected as part of a project establishing natural groundwater chemistry in aquifers across Scotland (Baseline Scotland). In autumn 2008, new groundwater samples were collected from boreholes abstracting from Carboniferous sedimentary aquifers across the Midland Valley. Four samples were collected of mine water, either pumped or flowing under gravity from abandoned mine workings. Two of the measured pumped minewater temperatures in the Baseline Scotland project were 11.7

and 14.5 °C, similar to the typical temperature of natural groundwater from Carboniferous aquifers in the Midland Valley. The third, at 19.2 °C, from Polkemmet, was pumped from an existing mine shaft, although the depth was not known. The single measured temperature of a gravity minewater flow was 9.8°C. The Coal Authority also has a database of passive discharges from abandoned mines in Scotland, which at the time Ó Dochartaigh had permission to use on the Baseline Scotland project. Only one of these recorded discharges is in Glasgow; on the outskirts in Swinton, by Coatbridge.

The single record for minewater temperature in Glasgow is the Highhouse Colliery, Bearsden (Northwest Glasgow, Figure 498). Here, a temperature of 18 ^{o}C was measured at 436 m depth (Gillespie et al., 2013). It is not clear to what degree this value is influenced by the temperature of the surrounding rocks.

5.4 HOT SEDIMENTARY AQUIFER (HSA) GEOTHERMAL

In places where aquifers of sufficient permeability and thickness exist at depth, heat energy can be extracted. The Midland Valley is the largest onshore area in Scotland to be underlain by sedimentary rocks (Gillespie et al., 2013) some of which might be aquifers at depth. However, their properties at depth are still largely unknown. Interpretation of temperatures is complicated by groundwater flow in areas of active coal mines. Aquifer properties are discussed above (Section 4). The geothermal potential of HSA was investigated by Browne et al. (1985) and Browne et al. (1987). They identified the possibility that the Knox Pulpit Formation could be buried beneath Glasgow, with thicknesses up to 170 m. The temperature at the top of the group was expected to exceed 40 ^{o}C. Where yield permits, heat pumps could be used to extract the heat energy. Other Carboniferous strata are considered to have limited HSA potential due to low intergranular permeability (Browne et al., 1985). However fractures might increase secondary permeability in some places.

5.5 FAULTS AND FLUID FLOWS

Faults can have a significant impact on subsurface temperatures due to their influence on rock permeability and resulting impacts on fluid flow pathways and heat transport. Faults are common throughout the Midland Valley. Faults can behave as pathways or baffles to water (or both simultaneously). Specific lithologies deform differently when subjected to stress, resulting in different permeability structures within fault zones.

Fault cores in (macroscopically) brittle rocks can comprise a combination of fault gouge, cataclasite, breccia, mylonite, discrete slip surfaces, and relatively cohesive lenses or blocks. Fault damage zones in brittle rocks tend to fracture, creating breccia or joints (Bense et al., 2013). Often, the damage zone around the fault core can be much more extensive and hydraulically more important, contributing more towards bulk permeability than the core (10's to 1000's of meters in thickness perpendicular to the fault strike compared with 0.1 to 10 m thickness). A model of fault hydraulic behaviour developed by Caine et al. (1996) projects the propensity for a fault to behave as a conduit/barrier according to the ratio of specific fault zone elements.

In clastic rocks, strain can be accommodated by (sometimes multiple) deformation bands in both the fault core and damage zone (Antonellini et al., 1995; Aydin, 1978). These are thin bands (<2 cm thickness) in which cataclasis and particulate flow occur (breakage and rolling/sliding of grains), acting to reduce pore space and thus permeability. Fractures are less common in these rocks. If there is a sufficient proportion of clay in the protolith of clastic rocks, clay can be smeared through the fault core, forming a seal of low permeability rock if continuous (Yielding et al., 1997). Clay smears can also be found in carbonate rocks. As a result of these processes, faults in clastic rocks often reduce permeability (Gibson, 1998).

Certain lithologies – carbonates in particular – may also be karstified, whereby permeability is increased further by the dissolution of the rock along fractures (Billi, 2005). Conversely, over time, mineral-saturated fluids can precipitate cements in pores and/ or fractures and effectively become re-sealed, reducing fault permeability (Micarelli et al., 2006) and forming baffles to fluid-flow. Each time the fault deforms (through tectonicstresses, or even due to stress peturbations such as unloading after glaciations or sub-surface stress changes) fractures may open and permeability can increase again (Knipe, 1997). Chemical reactions will begin again as groundwater enters the fractures. As a result, faults that have deformed more recently are more likely to be permeable. Barton et al. (1995) also found that normal faults optimally oriented to the current stress field, i.e. "critically stressed" and therefore more likely to slip, were also more permeable than those not critically stressed.

Browne et al. (1985) suggested most of the fault structures in the Midland Valley are normal faults, but high angle reversed faults also occur. They suggest that the history of the faults is complex and many structures have undergone different phases of movement. The truncation of some faults buried by younger sediments and volcanic rocks suggest that some became inactive after the early Carboniferous. In the Strathmore area, Devonian rocks are cut by sub-vertical orthogonal joint systems. Fault planes range from single slip planes to broken zones with associated fault breccias. Tests showed that water was usually derived from one or possibly two major fissure zones, with recharge either via fault zones or along dipping planes (Browne et al., 1985). Pumping tests and geophysical logs suggest that major water-bearing fissures occur down to depths of 125 m (Browne et al., 1985). The proximity of the coast and the Highland Boundary Fault may have caused groundwater to flow to effect the measured heat flow value at Montrose (Browne et al., 1987). No data have been located in the Glasgow area.

5.6 GEOTHERMAL DATA GAPS

In summary, there are no heat flow or temperature data in the Clyde Gateway area. 13 borehole temperature measurements in the 20 km area surrounding the Clyde Gateway area of interest indicate an average geothermal gradient of 30.2 ^{o}C/km with a surface temperature of 7.3 ^{o}C (Figure 49). Four heat flow measurements in the same area indicate a heat flow between 59.7 and 63.5 mW m^{-2} (standard deviation 5.4 and 5.9 mW m^{-2}). It has been suggested that heat flow measurements from shallow boreholes in the UK, such as those in Glasgow, have underestimated heat flow (e.g. Westaway and Younger, 2013; Busby et al., 2015). The impacts of palaeoclimates and recent warming on heat flow and geothermal gradients is therefore a key research question for assessing the geothermal potential of Glasgow, and other areas in the UK. This will require temperature and heat flow (and thermal conductivity) measurements at a range of depths throughout a number of deep (> 2 km depth) boreholes.

All heat flow measurements are currently from the north-west of Glasgow. There is only one temperature measurement in the south of Glasgow. Heat flow and temperature measurements in the south and east of the city, including in the Clyde Gateway area, would greatly improve the data coverage.

The single measurement of minewater temperature, at Highhouse Colliery in the north-west of Glasgow, was 18 ^{o}C at 436 m depth. It is not clear how closely this represents either the geothermal gradient, other minewater temperatures or temporal changes within mines. In order to properly assess minewater geothermal potential in Glasgow, additional temperature measurements in mine workings are needed with a good geographic spread and at different depths within the mines and over a sufficient time period in order to address these questions.

There is very little data available regarding the hydraulic behaviour of faults in the area of interest. Since faults can have a key role in controlling fluid flow pathways and patterns on a local and regional scale, elucicidation of their behaviour will be key to future investigations.

Due to the lack of hydrogeological and geothermal data for the study area it has not been possible to identify a geothermal or hydrogeological model for the Clyde Gateway area at this stage. However, one hypothesis is that the slightly higher geothermal gradient in Glasgow and the central Midland Valley might result from regional upflow of groundwater (Browne et al., 1987; Lee et al., 1987; Robins, 1988). This hypothesis could be used as a starting point for investigations. It would also be key to investigate the impact of mine workings on these natural flow pathways.

At this stage a geothermal feasibility study was not conducted due to the significant uncertainties associated with heat flow and temperature measurements in the area. However, there are a number which have attempted to do so (Ellen, et al., 2015; Ellen and Loveless, 2015; MacNab, 2011). Additional constraint of the geothermal properties of the area would enable realistic feasibility studies to be conducted for minewater potential and HSA.

6 Geochemistry and Land Quality

6.1 INTRODUCTION

This section summarises current knowledge on the geochemical environment of the land surface (0 – 0.5 m) in the Clyde Gateway area. It includes information on the geochemistry of stream sediment, stream water and shallow soil, but does not include information on the chemical quality of deeper geological deposits or of groundwater (See Section 4).

The chemical quality of land is an important consideration. Elemental concentrations at any location are controlled by factors such as geology, vegetation, soil forming processes and climate. In addition, environmental concentrations can be enhanced by anthropogenic (man-made) activities such as mining, industrialisation, urbanisation and waste disposal. The distribution of the elements is of concern because 26 are essential to life in small doses but are potentially harmful to plants and animals (including humans) in high doses and a further eight are generally toxic to most organisms. Of further concern are the quantities of persistent organic pollutants (POPs) mainly of man-made origin; many of which are detrimental to health. These include the polynuclear aromatic hydrocarbons (PAHs) and the polychlorinated biphenyls (PCBs) (Fordyce et al., 2012). Some natural rock types such as oil-shales, black algal limestones and black carbonaceous shales and coals are rich in PAHs; hence, their concentrations in underground water resources may be enhanced via contact with these rock types. There is the potential also to intersect liquid and gaseous hydrocarbons, whilst drilling in underground workings that have mined these types of deposit in the past (Appleton et al., 1995).

Substances of concern include also, naturally occurring radioactive materials (NORMS) such as uranium (U), thorium (Th) and potassium (K) and their radioactive decay products such as radium (Ra) and radon (Rn). Radium is relatively short lived, but radon is a natural colourless, odourless gas that is a daughter product of the radioactive decay of uranium in rocks, waters and soils. It can migrate up through rock, water and soil to the surface environment. Radon is a soil gas, but as it reaches the surface it has the potential to impact upon air quality also. Once in open air, radon is normally dispersed, but problems can arise if it enters confined spaces in poorly ventilated buildings where it can accumulate. As a radioactive substance, radon gas exposure has been implicated in lung cancer. The recommended action level in the UK for radon in homes is 200 Becquerels per cubic metre (200 Bq m^{-3}) (PHE, 2016).

Consideration has to be given also to other potentially harmful gases that occur in rocks, waters and soils such as methane (CH_4), carbon dioxide (CO_2) and hydrogen sulphide (H_2S). Methane is a low toxicity gas but when the concentration in air is between 5–15 % by volume, ignition will cause an explosion. It is highly flammable; hence potential hazards include fire and explosion. Methane is most commonly produced by the anaerobic breakdown of organic material in landfill or by geological processes such as the burial, compaction and heating of organic material, which is converted into methane-bearing rocks such as coal and oil-shales. Methane is only freely released from rocks either close to geological disturbances such as faults, or as a result of degassing as the coal/shale is fractured during mining. At high concentrations, carbon dioxide is toxic and asphyxiating. It can be produced by oxidation of coal/shale deposits and via biological processes. Carbon dioxide is produced also during oxidation of organic materials in landfill. Hydrogen sulphide is a toxic gas produced by the bacterial reduction of sulphate. Iron sulphide (FeS_2) is commonly associated with organic materials in UK coal-bearing and black shale rock types; hence, waters passing through these rocks are often rich in sulphate. Biological breakdown of this sulphate leads to the production of hydrogen sulphide gas. Hydrogen sulphide is produced also by the decomposition of organic matter in land-fill sites and in sewage works. All these gases are known to accumulate in former mine workings in the UK (Appleton et al., 1995). Methane, carbon dioxide and hydrogen sulphide released into open air are quickly diluted, but like radon, problems can arise if they enter poorly ventilated buildings or tunnels. Gas may migrate to the surface via natural faults and cracks as well as via man-made structures such as old coal workings, mine shafts, vents and boreholes. It can enter buildings via cracks in the floor, service ducts, sewerage systems, floor structures, claddings or ventilation ducts (Appleton et al., 1995).

The weathering/oxidation and biological breakdown of pyrite in coal and shale deposits also generates sulphuric acid (H_2SO_4) leading to acid mine-waters, which can have pH < 3. Many metal ions are more soluble in acid waters; hence acid mine drainage often contains elevated concentrations of metals such as iron, nickel, copper, lead, aluminium and manganese. When these waters reach the surface and (i) come into contact with oxygen in the air and (ii) dilution with surface waters raises the pH above 3; the iron precipitates out of the water as iron hydroxides, which form yellow-orange precipitates on stream beds. These can smother aquatic life and can contain elevated concentrations of other potentially harmful metals that precipitate out into the iron hydroxide phases (INAP, 2009).

The toxicity and mobility of all these potentially harmful substances (PHSs) are often controlled by the amount of other elements present, so it is important to understand as fully as possible the chemical composition of the environment. This is necessary to protect the quality of ecosystems and water bodies as well as plant, animal and human health under current UK environmental legislation (HMSO, 1990).

Under this legislation, before any development can take place, site assessments and ground investigations must be carried out to demonstrate that land quality is safe and fit for purpose for the intended use. In addition, the development of subsurface resources such as geothermal energy that have the potential to alter ground conditions should be monitored throughout their life cycle.

This section considers the current understanding of land quality in the Clyde Gateway area and the potential surface environmental impacts of GGERFS geothermal research.

6.2 STUDY AREA

Several factors contribute to the chemical quality of surface land and water resources in the Clyde Gateway area (Figure 51). These include natural factors (e.g. underlying bedrock and superficial deposit geology, vegetation, topography and climate) and anthropogenic factors (e.g. current and historic land use, particularly industry, waste disposal, power generation, atmospheric emissions and construction). A brief summary of these factors in the Clyde Gateway area is as follows.

6.2.1 Surface Water Bodies

The Clyde Gateway is bisected by the River Clyde, which flows east to west through the area into the Clyde Estuary. The Clyde Gateway area is upstream of the weir that limits the tidal extent of the river. Several smaller streams that flow into the River Clyde are located within the Clyde Gateway area also. These include the Battle, Camlachie, Eastfield, Malls Mire, Polmadie and Tollcross burns (Figure 51). However, for much of their length, these smaller streams are culverted and have only limited surface expression in the Clyde Gateway area (Fordyce et al., 2004).

6.2.2 Bedrock and Quaternary Geology

The Clyde Gateway area is underlain by a sequence of Carboniferous sedimentary rocks of the Scottish Coal Measures Group comprising repeated sequences of sandstone, siltstone, mudstone, seat-earth, shale, coal and ironstone. In the River Clyde corridor, these are overlain by Quaternary alluvial superficial deposits (Browne et al., 1999). Concentrations of PHS such as arsenic (As), antimony (Sb), beryllium (Be), cadmium (Cd), chromium (Cr), cobalt (Co), fluorine (F), iron (Fe), lead (Pb), mercury (Hg), nickel (Ni), uranium (U), and selenium (Se) can be enhanced in shale, coal and ironstones relative to other rock types; hence where these crop out at surface, the soils and sediments derived from them and water that passes through them can contain elevated concentrations of these chemical elements. However, it is difficult to discern relationships between the underlying geology and soil/sediment/surface water quality in the Clyde Gateway area as the surface environment has been highly altered by human activities (Fordyce et al., 2012).

6.2.3 Current and Historic Land Use

The Clyde Gateway area has a long history of development dating from the 18th century, with major expansion occurring during the 19th century (Glasgow City Archives, 2016). The area was home to several major industries including coal mining; brick, sand and gravel pits; print and paper works; textile and dye works; potteries; gas works and the former Dalmarnock coal-fired power station (Figure 52). The area was a centre for iron working in the past with major foundries on the western periphery of the area, in Parkhead in the north and on the south side of the River Clyde. The Clydebridge steel works continues to operate at the present day (Figure 52). JJ White’s, the world’s largest chromite ore processing plant during the 19th century, was located in the Shawfield area of the Clyde Gateway. The chromite ore was imported for processing and the plant operated until 1968. Chromite ore processing residues (COPR) were extensively used as landfill material around south-east Glasgow and it is estimated that 2 500 000 tons (dry weight) were deposited during the lifetime of the factory (Farmer et al., 1999). This has had an impact on the nature of artificial ground in the Clyde Gateway area (See Section 6.2.4). The former site of the chromite ore processing works at Shawfield has been the subject of a major remediation project over the last 10 years and this is described in more detail in Section 6.4.1.

The Clyde Gateway area was also home to extensive areas of 18^{th} and 19^{th} century sandstone-brick tenement housing, which was of poor quality. Since the Second World War, practically all of this housing has been demolished and replaced with a mixture of 1950–90s terrace, tenement and tower-block social housing. In the last 15 years, the Clyde Gateway area has been designated as a major area of urban regeneration. Under this programme, more of the Victorian-age tenements and some of the latter-20^{th} century housing as well as former industrial sites have been demolished to make way for new housing and commercial developments. The centrepiece for this redevelopment was the site of the 2014 Commonwealth Games, located in Dalmarnock. The Games were used as a vehicle to remediate former industrial land including the site of the old Dalmarnock power station and develop that into athlete's accommodation (converted to social housing after the Games), a multi-purpose arena, hotels and commercial developments.

As a result of these changes, today the Clyde Gateway area comprises a mix of residential housing, parks, sports facilities, light industry, heavy industry (the Clydebridge Steel works) and commercial developments (Glasgow City Archive, 2016).

6.2.4 Artificial Deposits

Given this complex history and multiple phases of redevelopment, the Clyde Gateway area is extensively underlain by artificial deposits. These comprise made and infilled ground composed of materials that may be natural or artificial in origin from both local and extraneous sources. Typically, artificial ground of this nature is only a few meters thick, but in areas close to former excavations, thicker deposits up to tens of meters may be expected (Browne et al., 1999). Materials such as building rubble, industrial waste, quarry waste and furnace slag are typically used as fill materials (McMillan and Powell, 1999) and depending on their composition can have an impact on soil and stream water and sediment chemistry. An example of this is the presence of chromite ore processing residue (COPR) in the Clyde Gateway area.

Many correspond to former brick and clay pits that were infilled in close proximity to the former JJ White's chromite works in the south of the Clyde Gateway area. As part of an extensive programme of remediation over the last 20 or so years, investigations into the nature of the COPR have been carried out and these are described in more detail in Section 6.4.1.

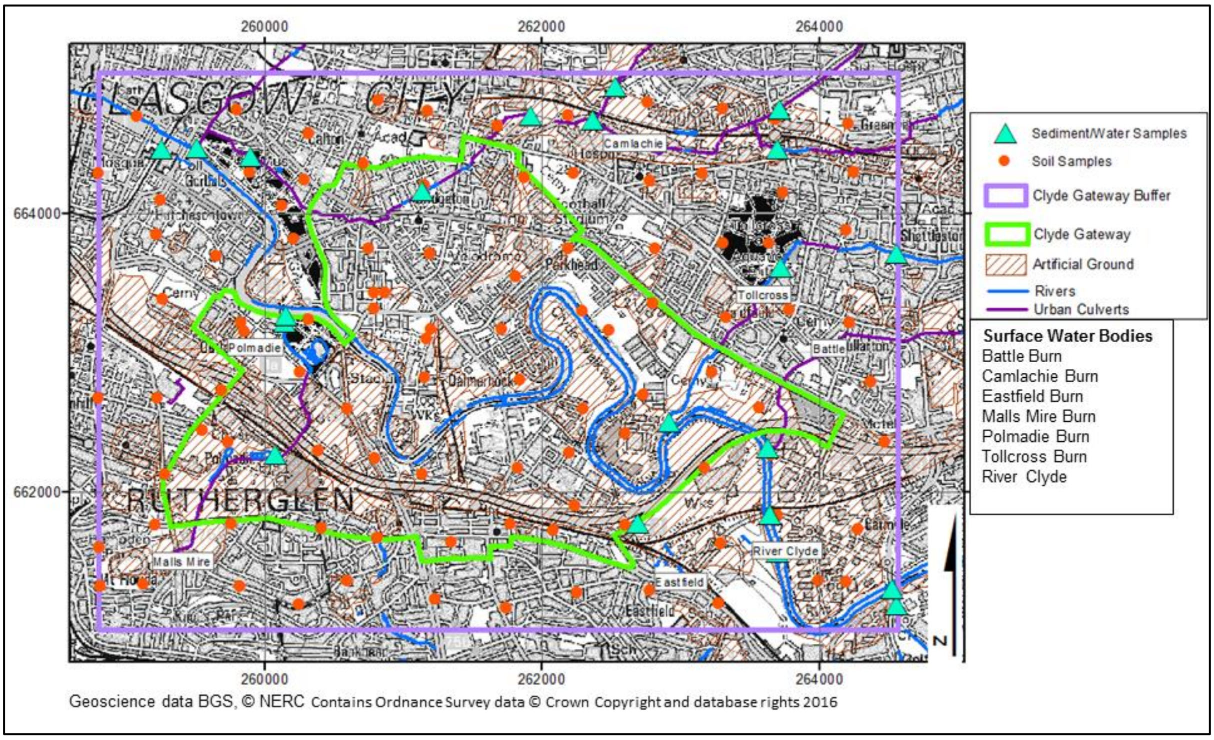


Figure 51 Location of BGS geochemistry samples in the Clyde Gateway area. Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2017. Licence number 100021290 EUL

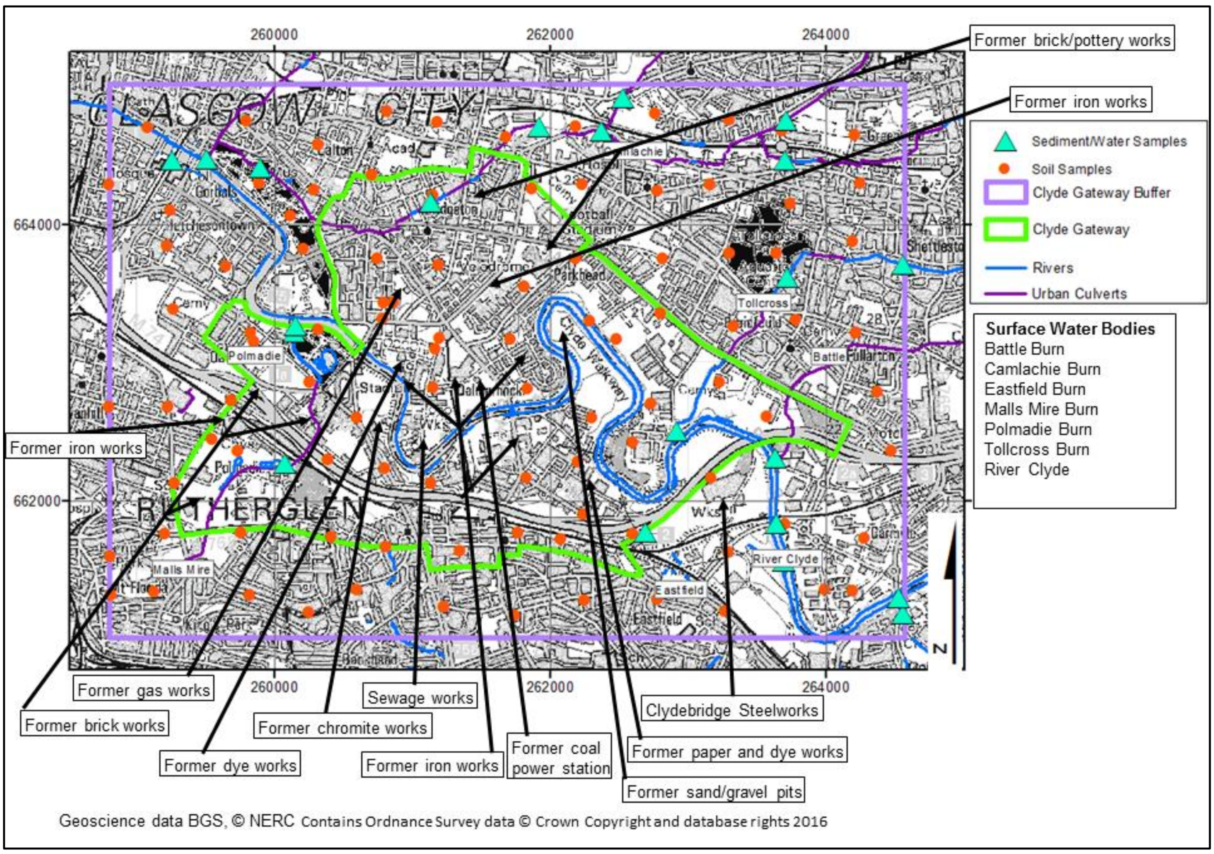


Figure 52 Location of selected current and historic land uses in the Clyde Gateway area. Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2017. Licence number 100021290 EUL

6.3 SOURCES OF INFORMATION ON LAND QUALITY IN THE CLYDE GATEWAY AREA

There are four main sources of information on the geochemistry of the surface environment in the Clyde Gateway area. These are:

1. British Geological Survey (BGS) – Public Health England (PHE) radon potential assessments
2. Site investigation reports held by Glasgow City Council (GCC) and South Lanarkshire Council (SLC)
3. Scottish Environment Protection Agency (SEPA) surface water quality monitoring data
4. Geochemical surveys carried out by the British Geological Survey (BGS) over the last 15 or so years

6.3.1 Natural Gases in Soil and BGS-PHE Radon Potential Data

The potential hazards from methane, carbon dioxide and hydrogen sulphide soil gas across the UK, including the Clyde Gateway area, were documented in a review of natural contamination carried out by the BGS for the Department of the Environment in the 1990s (Appleton et al., 1995). This review reports that historically, the South Lanarkshire coalfield was noted for a number of surface gas emissions, but these appear to have abated as a result of ventilation and dewatering during the development of deep mines after the 1850s (Robinson and Grayson, 1990). Carbon dioxide and hydrogen sulphide gases have been reported at an operational geothermal energy scheme accessing Scottish Coal Measure mine-waters at Cowdenbeath in Fife (Banks et al., 2009) and CO_2 emmissions from former coal-mine workings entering homes in two recent housing developments have been reported in Mid Lothian (Othieno, 2016). Other than the information contained within the Appleton et al. (1995) review, no systematic soil gas measurements have been identified within the Clyde Gateway area. Data may exist in site investigation reports held by GCC and SLC and it is recommended that these are assessed as part of a baseline monitoring strategy for the area.

For over 25 years, the BGS and PHE have collaborated to produce maps and datasets documenting potential threats of radon soil gas emissions in the UK. These are based on classifying the country according to the radon generating potential of different rock types depending on their likely uranium composition. This information is combined with data on radon levels in homes held by PHE to produce radon potential rankings for geological polygon areas across the country (PHE, 2016). Recently, the radon potential maps of Scotland have been revised to include the current 1: 50 000-scale geological linework (PHE-BGS, 2011). This highlighted a number of new areas designated as of high radon potential, particularly in the Central Belt of Scotland. In the last couple of years, PHE has been testing homes and schools in these areas to validate this prediction. The results of this most recent survey of radon in Scottish homes are due to be published within the next few months. Whether any homes have been surveyed within the Clyde Gateway area is unknown until the data are released, but the new report should provide estimates for likely radon concentration in the area once available.

6.3.2 Site Investigation Data

Information on the chemical quality of soil, sediment and surface water either from samples collected at surface or in boreholes is held in numerous site investigation reports held by GCC and SLC. Some of this information is held by BGS also, under varying levels of confidentiality. The benefit of this information is that samples are often collected at a closely spaced sampling density across any given development site. This provides detailed information on the variability of the chemical quality of land on a very local scale. This is important in urban environments where surface deposits are often highly heterogeneous.

The constraints on using this information are as follows:

1. As a research facility, the aim is for all UKGEOS data and information to be made publically available. Commercial site investigation chemistry information is held under a variety of confidentiality conditions. It’s important to note that land remediation and development will alter site chemistry and the validity of any site investigation data will change through time.
2. The information from site investigation reports is limited in its spatial extent by the distribution of sites where redevelopment has taken place. These tend to be along transport corridors and in designated regeneration sites rather than providing information for the whole area.
3. Chemical information held in site investigation records is often held in scanned pdf format and would require digitisation for use in scientific study. Digital records exist already for the Clyde Gateway area; even so, these would require organisation and checking prior to use. These tasks were beyond the scope of this initial assessment.
4. Chemical data from different site investigations may not be directly comparable. The experience that BGS has had using groundwater chemistry data from site investigation reports in the Clyde Gateway area for the Groundwater and Soil Pollutants (GRASP) project (Fordyce et al., 2014) is that samples from adjacent sites may have been collected and analysed in different ways in different laboratories. This makes comparison between adjacent sites difficult. Even when samples have been analysed by the same method in the same laboratory, but at different times, changes in calibration of the machines between analytical batches means that results may not be directly comparable. For example, concentrations of arsenic in soil from site A may be reported in the range 5–35 mg/kg whereas soil arsenic concentrations in an immediately adjacent site B may be reported as 10–80 mg/kg. The assumption would be that soils in site B contain more arsenic than site A. However, the apparent difference in results may be purely an artefact of different sampling and analytical methods and the arsenic content of both sites may be rather similar.

6.3.3 SEPA Surface Water Quality Monitoring Data

The SEPA has water quality monitoring stations on the River Clyde at Dalmarnock Bridge and Rutherglen Bridge within the Clyde Gateway area. They have two further stations, one at Cambuslang Road Bridge and one at the Clyde Tidal Weir immediately upstream and downstream of the Clyde Gateway area respectively. Time-series water quality monitoring data will be available from these stations, including parameters of interest to the baseline monitoring of environmental conditions for geothermal energy, including water temperature, pH, dissolved oxygen, total organic matter content (TOC) and a range of inorganic chemical parameters. It was beyond the scope of this initial assessment to request and review these data, but it is recommended that this should form part of further assessments of the Clyde Gateway area as these data should be publically available from the SEPA.

For reasons of time and ready availability of data, this report focusses on the systematic geochemical information that has been collected by the BGS across the Clyde Gateway area over the last 15 years.

6.3.4 BGS Geochemical Information

The BGS has carried out a number of systematic geochemical surveys of the surface environment in the Glasgow area over the last 15 years. These include three main sources of information on land quality in the area:

1. The Estuarine Contamination Project survey of sediment and water quality in the River Clyde Estuary
2. The G-BASE-GCC survey of stream sediment and stream water quality in all tributaries of the River Clyde within the GCC area – The Clyde Tributaries project
3. The Geochemical Baseline Survey of the Environment (G-BASE) soil survey of Glasgow

These projects provide information on the chemical quality of soils, stream sediments and waters within the Clyde Gateway area. Systematic projects such as G-BASE avoid the issues of differences between analytical runs outlined in Section 6.3.2, by careful quality control procedures, including the insertion of cross reference standards between analytical batches. Therefore, it is possible to assess the quality of the surface environment across the area using these datasets. For this report, and to place the Clyde Gateway area in the context of the immediate surroundings, a buffer zone of 0.5 km beyond the that of Clyde Gateway is used to assess the geochemical information from the three projects (Figure 51).

6.3.5 Clyde Estuary Sediment and Water Data

Water and grab sediment samples were collected at the same locations from the River Clyde as part of the BGS Estuarine Contamination project in 2003. Full details of the sampling and analytical methods are provided in Jones et al. (2004). The samples were analysed for a suite of approximately 50 inorganic and organic chemical parameters (Table 1). The Clyde Gateway and its buffer zone contain five water samples collected from the River Clyde, but only one of these is located within Clyde Gateway itself, at the junction of the Polmadie Burn with the River Clyde (Figure 51). None of the River Clyde sediment samples collected as part of this project lie within either the Clyde Gateway or Clyde Gateway buffer zone.

6.3.6 G-BASE-GCC Clyde Tributaries Stream Sediment and Water Data

Water and grab sediment samples were collected from the same locations from every kilometre of length of the tributaries draining into the River Clyde within the GCC area under a joint G-BASE-GCC Clyde Tributaries project in 2003. Full details of the sampling and analytical methods are provided in Fordyce et al. (2004). The samples were analysed for a suite of approximately 50 inorganic and organic chemical parameters (Table 17). Sixteen of the stream water samples are located within the Clyde Gateway and its buffer zone and of these, five are within the Clyde Gateway itself. These were collected from the Camlachie, Eastfield, Malls Mire, Polmadie and Tollcross burns (Figure 51). Where possible samples were collected from open sections of the streams, but in the cases of the Camlachie and Malls Mire burns, GCC provided assistance and manhole access for the collection of samples from culverted sections of the streams. In some cases there was no sediment present in the culverts at the time of sampling. Therefore, there are fewer sediment than water samples in the area; 13 in the Clyde Gateway buffer zone and four in the Clyde Gateway area (Figure 51).

6.3.6.1 G-BASE Soil Data

Top (5–20 cm) and deeper (35–50 cm) soil samples were collected from the same locations on a systematic 500 m grid sampling scheme across the Glasgow area by the G-BASE project in 2001–2002. This was part of a programme to characterise the chemical quality of urban soils across Glasgow. Full details of the sampling and analytical methods are provided in Fordyce et al. (2012). The samples were analysed for a suite of approximately 50 inorganic chemical parameters (Table 17). The G-BASE project carried out a further phase of work to characterise soil quality across the wider Clyde Basin in 2010–2011. As part of this programme, additional sampling was carried out in the Glasgow city area to determine organic contaminant (POP) concentrations in urban topsoils (5–20 cm). These Organic Pollutants in Urban Soil (OPUS) samples were collected from selected land use types and underwent total petroleum hydrocarbon (TPH), PAH and PCB analysis in addition to a full suite of inorganic parameter determinations (Table 17). Full details of the sampling and analytical methods are provided Kim et al. (In prep). As a result of these surveys, there are 100 G-BASE soil samples within the Clyde Gateway buffer zone and 41 within the Clyde Gateway area (Figure 51). Of these, seven OPUS samples with POP determinations are located in the Clyde Gateway area.

The numbers of BGS stream sediment, stream water and soil samples within the Clyde Gateway area are summarised in Table 18.

Table 17 Parameters determined in BGS stream sediment, stream water and soil samples in the Clyde Gateway area

Inorganic Parameters	Name	Units in Water	Units in Sediment	Units in Soil
Ag	Silver	NA	mg/kg	mg/kg
Al	Aluminium	µg/L	wt%	wt%
As	Arsenic	µg/L	mg/kg	mg/kg
Ba	Barium	µg/L	mg/kg	mg/kg
Be	Beryllium	µg/L	NA	NA
Bi	Bismuth	µg/L	mg/kg	mg/kg
Br	Bromine	NA	mg/kg	mg/kg
Ca	Calcium	mg/L	wt%	wt%
Cd	Cadmium	µg/L	mg/kg	mg/kg
Ce	Cerium	µg/L	mg/kg	mg/kg
Cl	Chlorine	mg/L	NA	NA
CN	Cyanide	NA	mg/kg	mg/kg
Co	Cobalt	µg/L	mg/kg	mg/kg
Cr	Chromium	µg/L	mg/kg	mg/kg
Cs	Caesium	µg/L	mg/kg	mg/kg
Cu	Copper	µg/L	mg/kg	mg/kg
DO	Dissolved Oxygen	mg/L	NA	NA
EC	Electrical Conductivity	µS/cm	NA	NA
F	Fluorine	mg/L	NA	NA
Fe	Iron	mg/L	wt%	wt%
Ga	Gallium	NA	mg/kg	mg/kg
Ge	Germanium	NA	mg/kg	mg/kg
HCO_3	Alkalinity	mg/L	NA	NA
Ho	Holmium	µg/L	NA	NA
Hf	Hafnium	NA	mg/kg	mg/kg
Hg	Mercury	µg/L	mg/kg	mg/kg
I	Iodine	NA	mg/kg	mg/kg
In	Indium	NA	NA	mg/kg
K	Potassium	mg/L	wt%	wt%
La	Lanthanum	µg/L	mg/kg	mg/kg
Li	Lithium	µg/L	NA	NA
Mg	Magnesium	mg/L	wt%	wt%
Mn	Manganese	mg/L	wt%	wt%
Mo	Molybdenum	µg/L	mg/kg	mg/kg
Na	Sodium	mg/L	wt%	wt%
Nb	Niobium	NA	mg/kg	mg/kg
Nd	Neodymium	NA	NA	mg/kg
Ni	Nickel	µg/L	mg/kg	mg/kg
NH_4	Ammonium	mg/L	NA	NA
NO_3	Nitrate	mg/L	NA	NA
P	Phosphorus	mg/L	wt%	wt%
Pb	Lead	µg/L	mg/kg	mg/kg
pH	pH	pH units	pH units	pH units
Rb	Rubidium	µg/L	mg/kg	mg/kg
Sb	Antimony	µg/L	mg/kg	mg/kg
Sc	Scandium	NA	mg/kg	mg/kg
Se	Selenium	µg/L	mg/kg	mg/kg
Si	Silicon	mg/L	wt%	wt%
Sm	Samarium	NA	NA	mg/kg
Sn	Tin	µg/L	mg/kg	mg/kg
SO_4	Sulphate	mg/L	NA	NA
S	Sulphur	mg/L	NA	mg/kg
Sr	Strontium	mg/L	mg/kg	mg/kg
Ta	Tantalum	NA	mg/kg	mg/kg
Te	Tellurium	NA	mg/kg	mg/kg
TDS	Total Dissolved Solids	mg/L	NA	NA
Th	Thorium	µg/L	mg/kg	mg/kg
Ti	Titanium	NA	mg/kg	mg/kg
Tl	Thallium	µg/L	mg/kg	mg/kg
U	Uranium	µg/L	mg/kg	mg/kg
V	Vanadium	µg/L	mg/kg	mg/kg
W	Tungsten	NA	mg/kg	mg/kg
Y	Yttrium	µg/L	mg/kg	mg/kg
Yb	Ytterbium	NA	NA	mg/kg
Zn	Zinc	µg/L	mg/kg	mg/kg
Zr	Zirconium	µg/L	mg/kg	mg/kg

Table 18 continued

Organic Parameters				
LOI	Loss on Ignition	NA	NA	wt%
PAH	Polycyclic Aromatic Hydrocarbons	NA	mg/kg	mg/kg
PCB	Polychlorinated Biphenyls	NA	µg/kg	µg/kg
TIC	Total Inorganic Carbon	mg/L	NA	NA
TOC	Total Organic Carbon	mg/L	wt%	NA
TBT	Tributyltin Tin	NA	mg/kg	NA
TPH	Total Petroleum Hydrocarbons	NA	mg/kg	mg/kg

NA = not analysed

Table 18 Number of BGS stream sediment, stream water and soil samples in the Clyde Gateway area

Sample Type	Clyde Gateway Buffer Zone	Clyde Gateway
Estuary River Clyde Sediment	0	0
Estuary River Clyde Water	5	1
Clyde Tributaries Stream Sediment	13	4
Clyde Tributaries Stream Water	16	5
G-BASE Topsoil (5 - 20 cm)	100	41
G-BASE Deeper Soil (35 - 50 cm)	90	33
G-BASE OPUS Topsoil (5 - 20 cm)	8	7

6.4 GEOCHEMICAL QUALITY OF THE CLYDE GATEWAY AREA SURFACE ENVIRONMENT

On the basis of the BGS geochemistry datasets, the chemical quality of stream sediment, stream water and soil is summarised as follows. In the absence of major changes in land use, the distribution of the majority of these chemical substances in soils and stream sediments are fairly stable through time; hence although the BGS surveys were carried out over 10 years ago; the results are likely to be representative of conditions on the ground today. Stream water chemistry is more variable through time and the data presented here are a spatial snapshot (See Section 6.4.3). Maps of parameter concentrations in BGS stream sediment, stream water and soil across the Clyde Gateway area are presented in Appendix 1.

When considering land quality it is useful to make comparisons to environmental guideline values that exist to protect ecosystems, aquatic bodies and plant animal and human health from exposure to PHS in the surface environment. The guidelines used for comparison in this assessment are outlined in Table 19. The soil quality guidelines are designed to protect against human exposure to soil and are land use specific. Called either generic assessment soil guideline values (SGV) or soil screening levels (SSL) these criteria represent the values below which land is not considered to be contaminated. Exceedance of the guideline does not mean that land is contaminated, rather that further investigations need to be carried out (EA, 2009; DEFRA, 2014).

6.4.1 Soil Quality

The concentrations of inorganic chemical parameters in topsoil (5–20 cm) across the Clyde Gateway area are presented as interpolated surface maps showing the data distribution, as there is systematic data coverage across the whole area. These were generated in an ArcMap® geographic information system (GIS) using the inverse distance weighting interpolation function, based on a grid size of 80 m and search radius of 500 m. Whilst the G-BASE soil sample density of 1 per 0.25 km^2 is relatively detailed for a city-wide survey; it is still not closely spaced enough to capture the variability in concentration for all the parameters due to the highly heterogeneous nature of urban soils. As such, there is a degree of uncertainty in extrapolating the data between known points and caution should be exercised when viewing the maps. Nonetheless, the maps provide an overview of soil geochemistry across the Clyde Gateway area. Only seven OPUS soil samples underwent POPs analysis in the area; hence, organic pollutant information is presented in the form of symbol maps.

Inorganic parameters were measured in deeper soil samples (35–50 cm) also. Whilst not the subject of this review due to time constraints, these show similar distributions to those in topsoil, but parameter concentrations vary between top and deeper soils across the area. In some cases, parameter concentrations can be higher in deeper soil due to the presence of artificial ground and waste materials. A fuller explanation of these relationships is given in Fordyce et al. (2012). This review focuses on topsoil (5–20 cm) chemistry as follows.

6.4.1.1 Inorganic Substances

Comparison of the 41 G-BASE topsoil samples from the Clyde Gateway area to the UK soil quality guidelines reveals that of the parameters listed in Table 19, concentrations in excess of the suggested allotment SSLs (91 mg/kg V; 620 mg/kg Zn) are reported in two allotment topsoils for vanadium and one for zinc (Fordyce et al., 2012). However, these are not UK legislative guidelines; rather they are proposed standards by the environmental consultancy industry and there is a deal of uncertainty in the derivation of these values (Nathanail et al., 2015). As such, exceedance of these SSLs does not equate to risk; rather that further studies may be advisable. Four soils contain cadmium concentrations above the UK allotment SSL of 1.8 mg/kg (DEFRA, 2014), but none are allotment soils; hence the guideline is not exceeded.

Higher soil-As concentrations in the Clyde Gateway area are associated with the present day industrial estate at Shawfield, which was the site of the former chromite ore processing works; and with the steel mill at Clydebridge (Figure 70 in Appendix 1). Arsenic and copper concentrations above the residential SSLs of 37 mg/kg (DEFRA, 2014) and 520 mg/kg (Nathanail et al., 2015) respectively are recorded at one site in Shawfield, but this is not a residential soil; hence the guidelines are not exceeded.

These areas also correspond to higher topsoil chromium (Figure 71 in Appendix 1), nickel (Figure 72 in Appendix 1) and lead (Figure 73 in Appendix 1) concentrations as a consequence of their metal processing history. Similarly, soil calcium contents are higher at these locations as lime was used in both chromite ore processing and steel production. The combination of high calcium-chromium-nickel is indicative of the presence of waste from these industries in the soils, which tends to be alkaline in nature (Figure 74 in Appendix 1). In other parts of the Clyde Gateway area, higher soil-lead concentrations are reported from a former gas works site and from artificial ground over a former reservoir (Figure 73 in Appendix 1); and higher soil chromium and nickel are associated with a former colliery, again reflecting historic land use (Figures 71 and 72 in Appendix 1).

Concentrations of nickel above the UK SGV of 130 mg/kg for residential land use (EA, 2009) are reported at six sites; however, none are residential soils; hence the guideline is not exceeded. For lead, two allotment soils exceed the SSL of 80 mg/kg and two residential soils exceed the SSL of 200 mg/kg (DEFRA, 2014). However, this does not mean that land is contaminated, rather that further investigations may be required.

Very high concentrations of soil-Cr (up to 4286 mg/kg) are reported in the Shawfield area associated with the COPR waste (Figure 71 in Appendix 1). Despite the presence of COPR in the area, only one allotment soil exceeds the former UK SGV of 130 mg/kg for this land use type. Similarly, only one domestic garden soil exceeds the former UK SGV for Cr in residential soils of 200 mg/kg (EA, 2002). In terms of toxicity, the speciation of chromium is important. Under natural conditions, chromium is normally present as the CrIII form and is an essential trace element for health. However, the CrVI hexavalent form is a known carcinogen to humans via inhalation. CrVI is rare in natural environments, but is generated by industrial processes. Therefore, the old SGVs have been superseded by SSL that take into account the speciation of Cr and the concentration of CrVI in particular (DEFRA, 2014). The G-BASE dataset does not contain information on the CrVI content of soil, but the former chromite ore works site at Shawfield has been the subject of much study and a major regeneration programme over the last 15 or so years. Work by Bewley et al. (2001) and Hillier et al. (2003) revealed that the COPR material was over 10 m thick in places and was highly alkaline and soluble and contained very high concentrations of both CrIII (up to 49 500 mg/kg) and CrVI (up to 15 600 mg/kg).

Broadway et al. (2010) investigated CrVI concentrations in 21 of the highest total-Cr concentration G-BASE Glasgow urban topsoils and a further six samples collected from known COPR waste sites. Results revealed that CrVI concentrations ranged between < 1.89–1485 mg/kg. However, concentrations in excess of the new most precautionary (residential land use) DEFRA (2014) SSL of 21 mg/kg CrVI were present in three of the topsoils from the known Cr-waste sites only. None of these soils were from residential land uses. Two of the samples were located at Shawfield in the Clyde Gateway area. Further tests to examine possible human bioaccessibility via the ingestion exposure route showed that CrVI in the soil was reduced to CrIII in the gut and was of less concern for human uptake. However, simulations of inhalation exposure on two of the Cr-waste soils, suggested that CrVI may be bioavailable. Hence, inhalation of polluted dusts may be a potential consideration in the area (Broadway et al., 2010).

The Cr-waste sites in Glasgow have undergone significant remediation in recent years including lining and diverting of water courses away from the waste dumps, in situ chemical treatments with calcium polysulphide and capping/containment of the waste materials to mitigate the impacts on soil and water quality and human interaction (Bewley and Sojka, 2013). This work has taken place since the G-BASE survey was carried out in 2001–2002; hence soil-Cr concentrations may now be lower in the area.

6.4.1.2 Persistent Organic Pollutants (POPs)

Comparison of the seven G-BASE OPUS topsoil samples from the Clyde Gateway area to the UK soil quality guidelines reveals that of the parameters listed in Table 19, none of the soils exceed current UK POPs guidelines for the particular land use.

The distribution of total petroleum hydrocarbons (TPH) across the area is shown in Figure 75 in Appendix 1. However, no soils are above the suggested most precautionary SSL for TPH of 1200 mg/kg (residential land use) (Nathanial, et al., 2015). Highest concentrations are associated with soil from a road verge adjacent to a petrol station at a busy road junction; soil from a former gas works site and soil from an allotment on artificial ground over a former reservoir. This map gives some indication of TPH concentrations in the surface environment. This is an important baseline dataset since geothermal boreholes are likely to access waters in contact with coal and shales, which may contain naturally higher TPH contents than other rock types.

Concentrations of the PAH benzo(a)pyrene are above the UK residential SSL of 3 mg/kg (DEFRA, 2014), in two soils, but neither were collected from residential land use, so the guideline is not exceeded. One is from a former gas works site and the other from an allotment on artificial ground over a former reservoir (Kim et al., In Prep) (Figure 76 in Appendix 1). Concentrations of topsoil dibenz(a,h)anthracene are higher than the suggested SSL for residential land use of 0.3 mg/kg (Nathanail et al., 2015) at these sites also and at the site of a petrol station road verge, but again none are residential land uses; hence, the guideline is not exceeded (Figure 77 in Appendix 1).

6.4.2 Stream Sediment Quality

There are no freshwater sediment quality regulations for the UK, but comparison of the Clyde Gateway area sediments with the Canadian guidelines reveals that of the parameters listed in Table 19, the probable effect concentration (PEC) to protect aquatic life is exceeded by chromium in the Camlachie, Polmadie, Malls Mire and Eastfield Burns. All these streams drain areas of COPR waste disposal; hence the elevated values. Very high concentrations of 2345 mg/kg are reported in the Polmadie Burn which drains the former chromite ore processing works site at Shawfield (Figure 78 in Appendix 1). Whalley et al. (1999) investigated chromium concentrations in sediments from 13 sites from the upper reaches of the River Clyde catchment to the Inner Estuary and found similarly high concentrations in sediments in the Polmadie Burn (3600 mg/kg) and River Clyde (6600 mg/kg) immediately downstream of the Polmadie Burn. High concentrations of chromium in sediment were evident up to 1 km downstream of this input.

However, since these studies have taken place the Shawfield site has been extensively remediated (see Section 6.4.1). Since the remediation, Palumbo-Roe et al. (2013) have carried out determinations of chromium speciation in sediment pore waters in the Polmadie Burn to assess its mobility from the polluted sediments into the water column. Interestingly, CrVI concentrations were low in the sediment pore water, despite very high total chromium concentrations (up to 12 500 mg/kg) in the sediment. This indicates that high-Cr bearing sediment is still present downstream of the Shawfield site in the Polmadie Burn, but that this may not be readily mobilised into the water column. An ongoing joint PhD studentship between Edinburgh University and the BGS is examining these relationships further, exploring chromium speciation in sediment, pore water and stream water in the Polmadie Burn to improve understanding of chromium mobility and pollutant migration in such post-industrial settings (Sim et al., 2015).

Geothermal energy research is unlikely to impact upon sediment quality directly, beyond the concerns of increased sedimentation during any construction process that disturbs the ground. It may have an indirect impact only if (i) there is connectively between the groundwater resources utilised and the surface water system and (ii) hydrogeological and hydrological flow regimes are changed.

6.4.3 Stream Water Quality

Neither surface water nor groundwater in Glasgow are used as a drinking water resource. Hence, the main concerns for water quality centre on ecological protection under the Water Framework Directive (WFD) (CEC, 2008). The BGS Clyde Estuary and G-BASE-GCC Clyde Tributary stream water samples were collected across the Glasgow area during 2002 and provide a spatial overview of stream water quality (Fordyce et al., 2004; Jones et al., 2004). However, samples were collected only once and as such are a spatial snapshot. Time-series monitoring would be required to provide baseline water quality information for GGERFS as water quality changes in response to factors such as climate, weather, season, flow and storm events.

As an initial assessment, comparison of the BGS surface water chemistry results to the WFD freshwater Environmental Quality Standards (EQS) indicates that for the substances outlined in Table 19, only ammonium, chromium, phosphorus and dissolved oxygen (DO) exceeded the guidelines as follows.

Ammonium, chromium, phosphorus concentrations are above the recommended EQS and DO below the recommended EQS in the Polmadie Burn (Figures 79–82 in Appendix 1). This stream drains the former chromite ore works site in Shawfield; hence the high concentrations of Cr in the burn water (126 µg/L) and elevated values in the River Clyde water at the tributary junction with the Polmadie Burn (5 µg/L). Indeed, very high concentrations of Cr (9100 µg/L) have been reported in groundwater at the Shawfield site resulting in very elevated values (6700 µg/L) in the Polmadie waters and 1100 µg/L in the River Clyde (Farmer et al., 2002). Similarly, Cr concentrations of 16 9000 µg/L in groundwater and 3100–6200 µg/L in stream waters from the Polmadie Burn were reported from the site by Whalley et al. (1999). By contrast, Cr concentrations in samples of river water from 13 sites along the River Clyde were below the limit of detection with the exception of waters immediately downstream of the Polmadie Burn inflow, which contained 1100 µg/L. At sampling points 1 and 4 km downstream of the inflow, values of 10 µg/L were recorded indicating rapid dilution of the stream water inputs in the river system. The studies by Farmer et al. (2002) demonstrated that >90 % of the Cr present in south-east Glasgow was in the more toxic CrVI hexavalent form and was associated with humic substances in the waters. Similarly, Whalley et al. (1999) showed that the groundwaters from the Shawfield site, stream waters from the Polmadie Burn and River Clyde waters downstream of the Polmadie Burn contained Cr in the more toxic hexavalent form. However, since these studies and the BGS surveys have taken place, the Shawfield site has been extensively remediated (see Section 6.4.1).

Within the Clyde Gateway area, high chromium concentration above the EQS is reported also in the Eastfield Burn water, which drains another area of COPR waste (Figure 80 in Appendix 1). Phosphorus exceeds the EQS also in the Malls Mire, Eastfield and Tollcross Burns probably because these urban streams are culverted for significant parts of their length (Figure 81 in Appendix 1). This restricts sunlight and oxygenation, which in turn limit biological nutrient processing. For similar reasons, DO is lower than the recommended EQS in these streams and the Battle Burn (Figure 82 in Appendix 1).

There are no freshwater EQS for uranium in water in the UK; however, none of the stream water samples in the Clyde Gateway area exceed the Canadian freshwater EQS of 15 µg/L (Figure 83 in Appendix 1). It is important to consider uranium in water, as deep mine-waters in rock sequences containing coal and shale that may contain elevated concentrations of NORMs such as uranium.

Stream water pH in the Clyde Gateway area is circum neutral to alkaline (pH 6.8–8.3) and above the recommended EQS (Figure 84 in Appendix 1). Acid mine drainage (AMD) is often associated with coal mining and is a consideration in geothermal development in general based on mine-waters (Banks et al., 2009). However, if present, this is only likely to impact on surface water quality if there is connectivity between groundwater and surface water resources. It will be important to establish these relationships and baseline conditions prior to any geothermal research.

Table 19 Stream water, stream sediment and soil environmental quality guidelines used in the present assessment

Substance	UK Freshwater EQS	Canadian < 2 mm Freshwater Sediment PEC	UK SGV/SSL for Residential (R) /Allotment (A) Soils
Reference	CEC (2008)* UKTAG (2010)# EA (2013a)` CCME (2011)¬	MacDonald et al. (2000)	EA (2002)~ EA (2009)+ DEFRA (2014)^ CL:AIRE (2010)” Nathanial et al. (2015)$
Arsenic (As)	50 µg/L#	33 mg/kg	37 mg/kg (R)^
Antimony (Sb)			550 mg/kg (R)”
Barium (Ba)			1300 mg/kg (R)”
Cadmium (Cd)	0.09 µg/L*	4.98 mg/kg	1.8 mg/kg (A)^
Chromium (Cr)	4.7 µg/L#	111 mg/kg	130 mg/kg (A)~ 200 mg/kg (R)~
Copper (Cu)	10 µg/L#	149 mg/kg	520 mg/kg (A)$
Iron (Fe)	1 mg/L#		
Lead (Pb)	7.2 µg/L*	128 mg/kg	80 mg/kg (A)^ 200 mg/kg (R)^
Mercury (Hg)	0.05 µg/L*	1.06 mg/kg	1 mg/kg (R)^
Molybdenum (Mo)			670 mg/kg (R)”
Nickel (Ni)	20 µg/L*	48.6 mg/kg	130 mg/kg (R)+
Nitrate (NO_3)	30 mg/L`		
Phosphate (P_2O_5)	0.1 mg/L`		
Selenium (Se)			120 mg/kg (A)+
Uranium (U)	15 µg/L¬		
Vanadium (V)			91 mg/kg (A)$ 410 mg/kg (R)$
Zinc (Zn)	75 µg/L#	459 mg/kg	620 mg/kg (A)$
Ammonium (NH_4)	1 mg/L (Fisheries)*		
PAH		22.8 mg/kg	
PCB		676 µg/kg	
TPH			1200 mg/kg (R)$
Benzo(a)pyrene (BaP)			3 mg/kg (R)^
Dibenz(a,h)anthracene (DAB)			0.3 mg/kg (R)$
pH	6.5 (Class 2)*		
Dissolved Oxygen (DO)	6 (Class 2)*		

EQS = Environmental Quality Standard SSL = Soil Screening Level Class 2 = Class 2 rivers

PEC = Probable Effect Concentration SGV = Generic Assessment Criteria Soil Guideline Value

Footnote: The most recent soil protection legislative guidelines are the SSLs for arsenic, cadmium, chromium (Cr) VI, lead, mercury and benzo(a)pyrene (BaP) (DEFRA, 2014). The previous SGVs for nickel and selenium are still in use also (EA, 2009). Reference is made here to the former total chromium SGV because CrVI was not analysed in the G-BASE dataset. Similarly, the G-BASE dataset contains no information on mercury soil concentrations. In addition, to the SSL and SGVs listed above, the environmental consultancy industry has proposed SSLs for antimony, barium, copper, molybdenum, vanadium, zinc and dibenz(a,h)anthracene (DAB) (CL:AIRE, 2010; Nathanail et al., 2015). Whilst these are commonly used in site investigation practice, they are not UK legislative guidelines.

7 Engineering Geology (Geotechnical data)

This section provides an assessment of the geotechnical data for the different lithostratigraphical units that are present within a rectangular area enclosing the Clyde Gateway area (SW corner 258000, 660850, NE corner 265000, 665000) within the BGS National Geotechnical Properties Database (NGPD). Where there is little data available for a unit, a wider area was used. This focused primarily within the central Glasgow area (NS56SE, NS56NE, NS66SW and NS66NW, 255000, 660000 to 265000, 670000) as this is where most of the data are located. A summary of the engineering geological descriptions of the superficial deposits and bedrock unit lithologies are in Tables 20 and 21 respectively.

The superficial deposits and bedrock geological units considered here are:

Superficial deposits:

Clyde Valley Formation (Law Sand and Gravel Member);
Gourock Formation;
Killearn Sand and Gravel Member;
Paisley Clay Member;
Bridgeton Sand Member;
Broomhouse Sand and Gravel Formation (including clay facies);
Ross Sand Member;
Bellshill Clay Member;
Wilderness Till Formation

Bedrock:

Scottish Upper Coal Measures Formation;
Scottish Middle Coal Measures Formation;
Scottish Lower Coal Measures Formation;
Passage Formation;
Upper Limestone Formation;
Limestone Coal Formation;
Lower Limestone Formation;
Western Midland Valley Westphalian to Early Permian Sills

The graphs presented in this section (below) and Appendix 2 provide the basic summary geotechnical data for the majority of the units that will be encountered by any potential boreholes in the Clyde Gateway area. There was little data for the Law Sand and Gravel Member, Lower Limestone Formation and no data for the Lawmuir or West Lothian Oil-Shale formations. Analysis of the anthropogenic deposits was not included as they are highly variable and site specific assessment is preferable. This could be undertaken once specific sites are delineated for the Clyde Gateway baseline and monitoring boreholes.

Engineering geological classification	Engineering Geological Description	Lithostratigraphical units
Organic deposits	Highly compressible organic deposit	Peat
Mixed fine and coarse-grained deposits	Highly variable, very soft to very stiff, very loose to very dense, clay, silt, sand, gravel, cobble and or boulders of natural and man-made materials.	Anthropogenic deposits
	Loose to medium dense SAND and GRAVEL or soft to firm (stiff) CLAY or SILT	Gourock Formation Head
	Firm to very stiff gravelly sandy CLAY with occasional cobbles and boulders or very dense SAND and GRAVEL or firm to stiff CLAY or SILT	Wilderness Till Formation Baillieston Till Formation
Fine deposits	(Very soft) soft to firm laminated sometimes sandy SILT or CLAY with occasional gravel	Lacustrine deposits Strathkelvin Silt and Clay Member Linwood Clay Member Paisley Clay Member
	Firm to stiff (very stiff) sometimes laminated CLAY/SILT	Bellshill Clay Member Broomhill Clay Formation
Coarse deposits	Loose SAND, gravelly SAND, sandy GRAVEL or GRAVEL	Law Sand and Gravel Member
	Loose to dense (silty) SAND or SAND and GRAVEL	Killearn Sand and Gravel Member Ross Sand Member Bridgeton Sand Member
	Medium dense to very dense SAND/GRAVEL occasional boulders	Broomhouse Sand and Gravel Formation Broomhouse Sand and Gravel Formation (sand facies) Cadder Sand and Gravel Formation Sand and Gravel (Undifferentiated)

Table 20 Engineering geological classification of the Clyde Gateway area superficial deposits.

Geological Formation	Rock type	Engineering description
Western Midland Valley Westphalian to Permian Sills (WMVAS)	Olivine dolerite and olivine microgabbro	Medium strong to extremely strong, greenish grey or greyish black DOLERITE/BASALT sometimes close to widely spaced horizontal discontinuities.
Upper Coal Measures Scotland Formation (UCMS)	Sandstone	Weak to medium strong, sometimes very strong, laminated to medium bedded, pinkish grey, reddish grey, greyish pink, sometimes purple mottled, fine to medium SANDSTONE.
	Siltstone	Very weak to medium strong, laminated, purplish brown, red, greyish green, reddish grey SILTSTONE
	Mudstone	Very weak to weak (sometimes medium strong very occasionally strong (seatearth), laminated MUDSTONE
Middle Coal Measures Scotland Formation (MCMS)	Sandstone	Weak to very strong sometimes very weak or extremely strong, laminated to thickly bedded, white to greyish white fine to coarse SANDSTONE
	Siltstone	Very weak to medium strong, sometimes strong, laminated, grey to black SILTSTONE
	Mudstone	Extremely weak to medium strong, thinly laminate to medium bedded, grey to black MUDSTONE
	Ironstone	Strong to extremely strong, sometimes medium strong, grey or grey brown to pale yellowish brown IRONSTONE.
	Coal	Extremely weak to medium strong, black COAL.
Lower Coal Measures Scotland Formation (LCMS)	Sandstone	Very weak to very strong, white to grey, laminated to medium bedded, greyish white to grey, fine to medium SANDSTONE.
	Siltstone	Weak to medium strong (sometime extremely weak to very weak or strong), laminated, grey to black SILTSTONE
	Mudstone	Extremely weak to medium strong, occasionally strong, thinly sometimes medium bedded, grey to dark grey MUDSTONE
	Coal	Extremely weak to very weak, black COAL
Passage Formation (PGP)	Sandstone	Medium strong to strong, sometimes very weak, white to grey fine to medium SANDSTONE.
	Siltstone	Weak to medium strong, sometimes strong, light grey to grey SILTSTONE
	Mudstone	Extremely weak to medium strong, thinly laminated to thinly bedded, grey to dark grey, greyish brown, MUDSTONE
	Coal	Extremely weak to weak, black COAL
	Limestone	Medium strong to strong, grey or dark grey, sometimes greenish grey, sometimes with closely spaced vertical and subhorizontal sand filled joints, LIMESTONE

Upper Limestone Formation (ULGS)	Sandstone	Weak to very strong, greyish white to grey, sometime brownish grey, fine to medium SANDSTONE
	Siltstone	Weak to medium strong, thinly to thickly laminated to sometimes thickly bedded, grey SILTSTONE.
	Mudstone	Very weak to medium strong occasionally strong, laminated to thickly bedded, sometimes jointed grey to dark grey MUDSTONE. Joints sometimes medium space and rough.
	Coal	Extremely weak to very weak, sometimes fractured, black COAL
	Limestone	Medium strong to very strong, sometimes jointed, grey to dark grey LIMESTONE.
Limestone Coal Formation (LSC)	Sandstone	Weak to very strong, (sometimes very weak or extremely strong), light grey to greyish white, fine to coarse SANDSTONE. Sometimes with calcite veins.
	Siltstone	Very weak to strong occasionally very strong, laminated, thinly to thickly bedded grey SILTSTONE
	Mudstone	Extremely weak to medium strong, sometimes jointed, generally laminated, grey, dark grey or black, sometimes greyish brown MUDSTONE. Joints are smooth to rough.
	Coal	Extremely weak to medium strong, or very strong when burnt,
	Seatearth	Extremely weak to strong, grey, sometimes brecciated, SEATEARTH.
	Limestone	Medium strong top very strong, grey, sometimes argillaceous, LIMESTONE
	Ironstone	Strong to extremely strong, sometimes medium strong, thickly laminated, pale brown, brown or black, sometimes colour banded IRONSTONE sometimes with mudstone band.
Lower Limestone Formation	Sandstone	Medium strong to strong, thin to medium bedded, sometimes with thin siltstone or mudstone beds, pale to very pale grey or grey brown to yellow brown (weathered) SANDSTONE
	Siltstone	Medium strong to strong, sometimes with thin bedding, dark grey SILTSTONE.
	Mudstone	Extremely weak to medium strong occasionally strong, sometimes widely jointed, sometimes laminated, grey to dark grey or black. MUDSTONE. Joints are generally undulating and smooth.
	Coal	Extremely weak to very weak, fractured, black COAL
	Limestone	Strong to very strong, grey, generally argillaceous LIMESTONE
	Ironstone	Very strong, sometimes with slightly undulating

		to rough planar joints, light grey to grey fine IRONSTONE

Table 21 Engineering geological descriptions of the Clyde Gateway area bedrock units and their lithologies

7.1 BEDROCK PERMEABILITY

One of the parameters of great interest for Clyde Gateway area is permeability, or, as measured in ground investigations, hydraulic conductivity. There are 31 values for the Clackmannan Group (Passage to Lower Limestone formations) and Scottish Coal Measures Group within the Clyde Gateway area, and a total of 34 values. All the values are shown in Figure 53 for the different lithologies and geological formations.

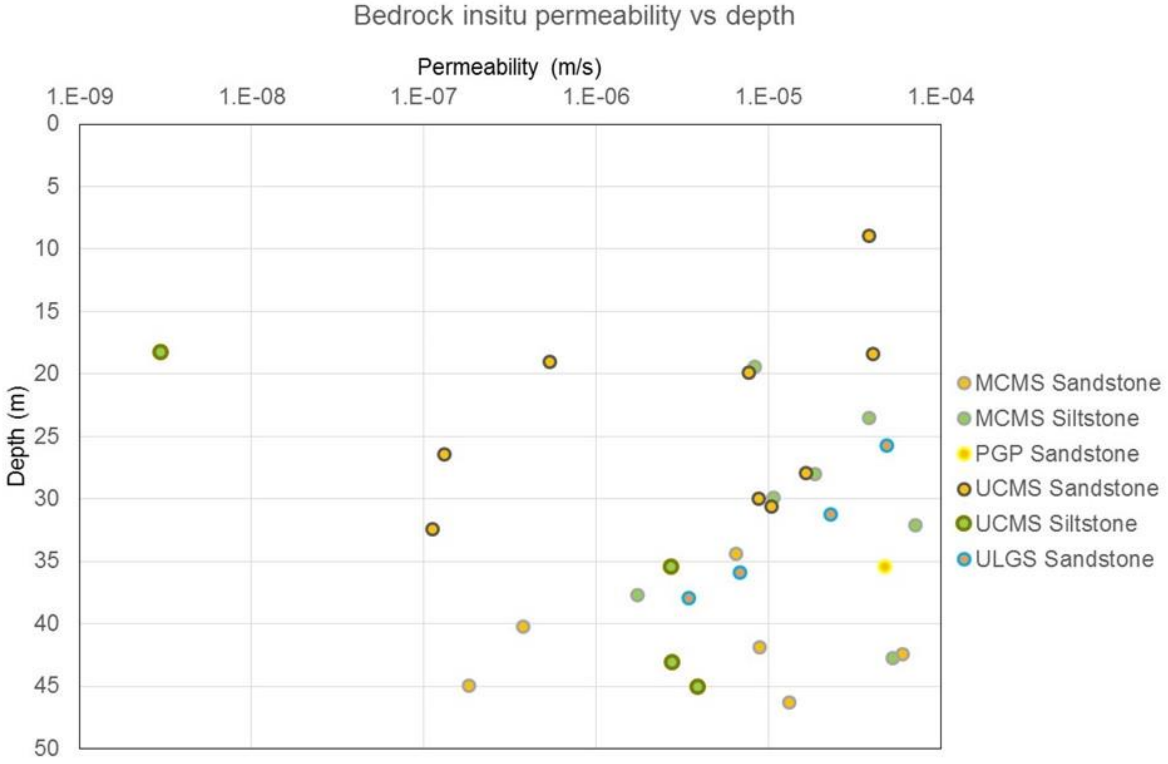


Figure 53 In situ permeability values vs depth for the Clyde Gateway area

7.2 POROSITY

Other parameters that might be used to indicate permeability include porosity, pore size, pore connectivity and the characteristics of mechanical discontinuities, for example joints. The laboratory porosity test measures connected pores (effective porosity). The particle size of the rock is indicative of pore size, in decreasing pore size sandstone > siltstone > mudstone. However, there is little bedrock porosity data available but porosity can be related to dry density via the particle density.

$$e = (\rho_s/\rho_d) - 1 \qquad (1)$$

$$n = e/(1+e) \qquad (2)$$

Where e is voids ratio, and the relationship between porosity, ρ_s is the density of the particles, ρ_d is the dry density and n is porosity. The dry density vs depth for each of the bedrock units are in Figure 544 to 58.

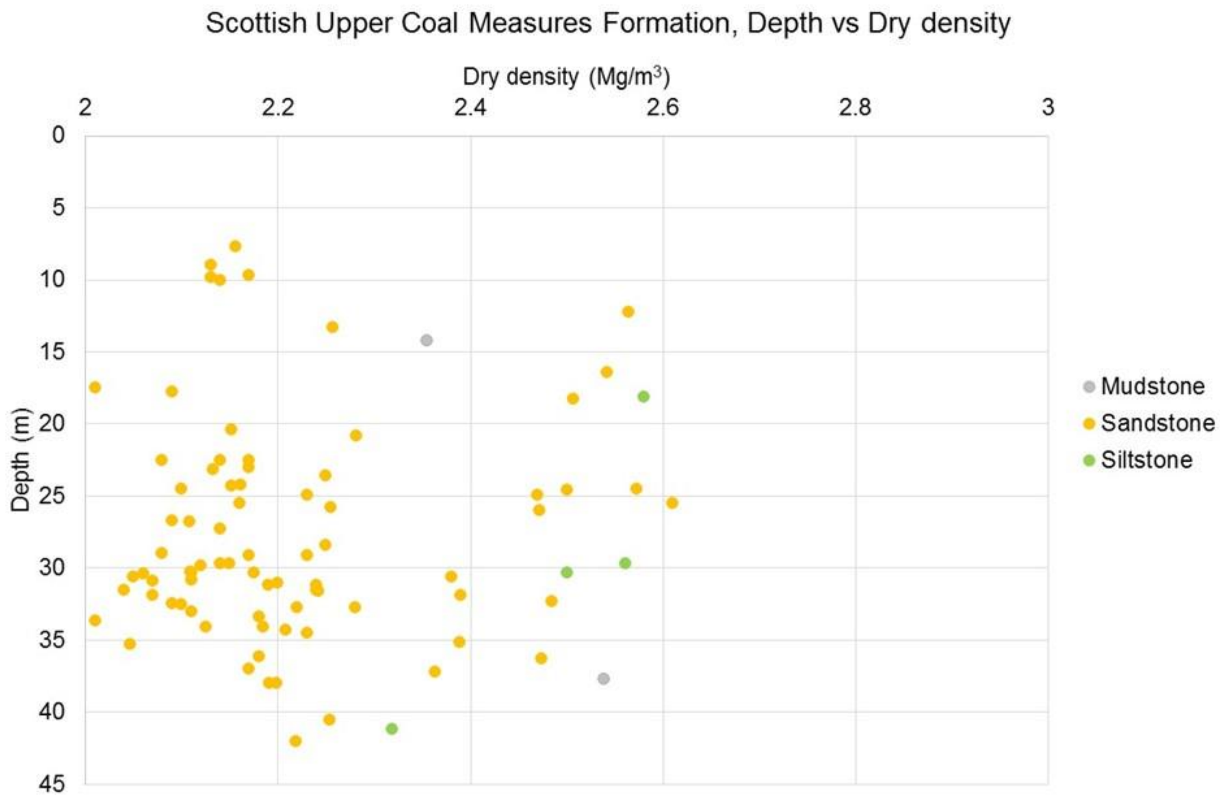


Figure 54. Scottish Upper Coal Measures Formation, the dry density at depth below ground level

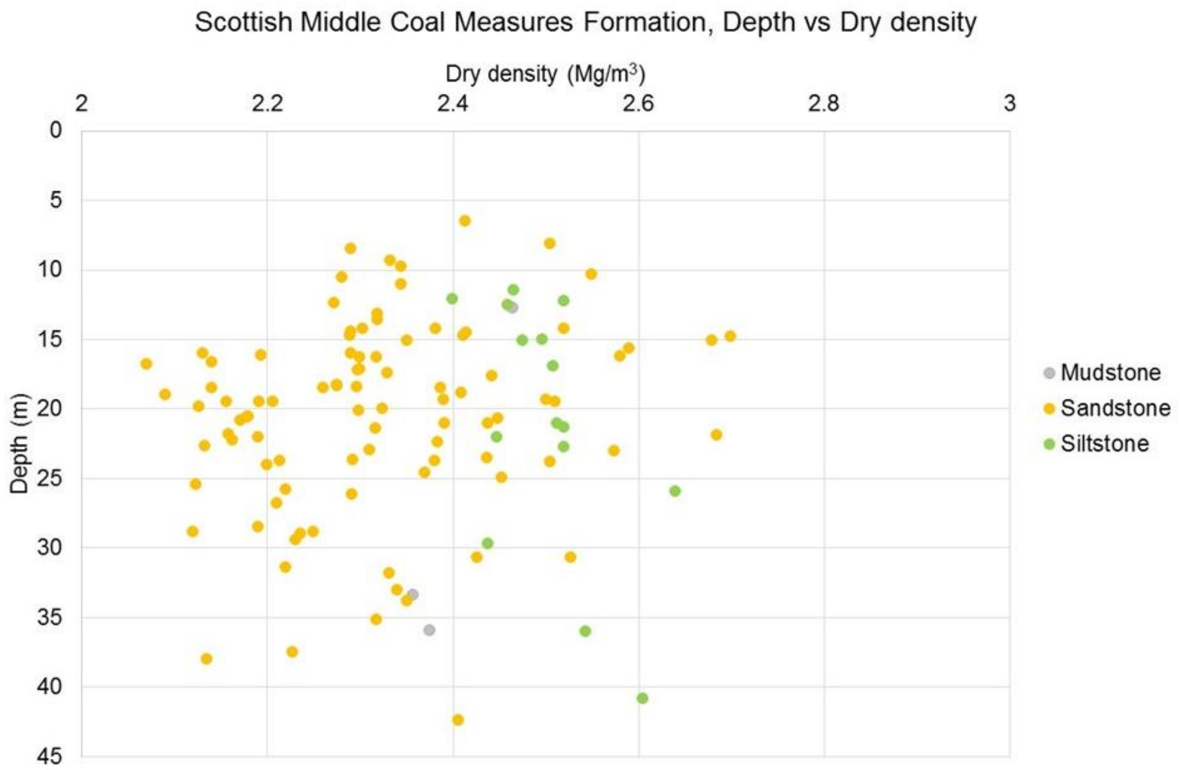


Figure 55. Scottish Middle Coal Measures Formation, the dry density at depth below ground level

Figure 56. Scottish Lower Coal Measures Formation, the dry density at depth below ground level

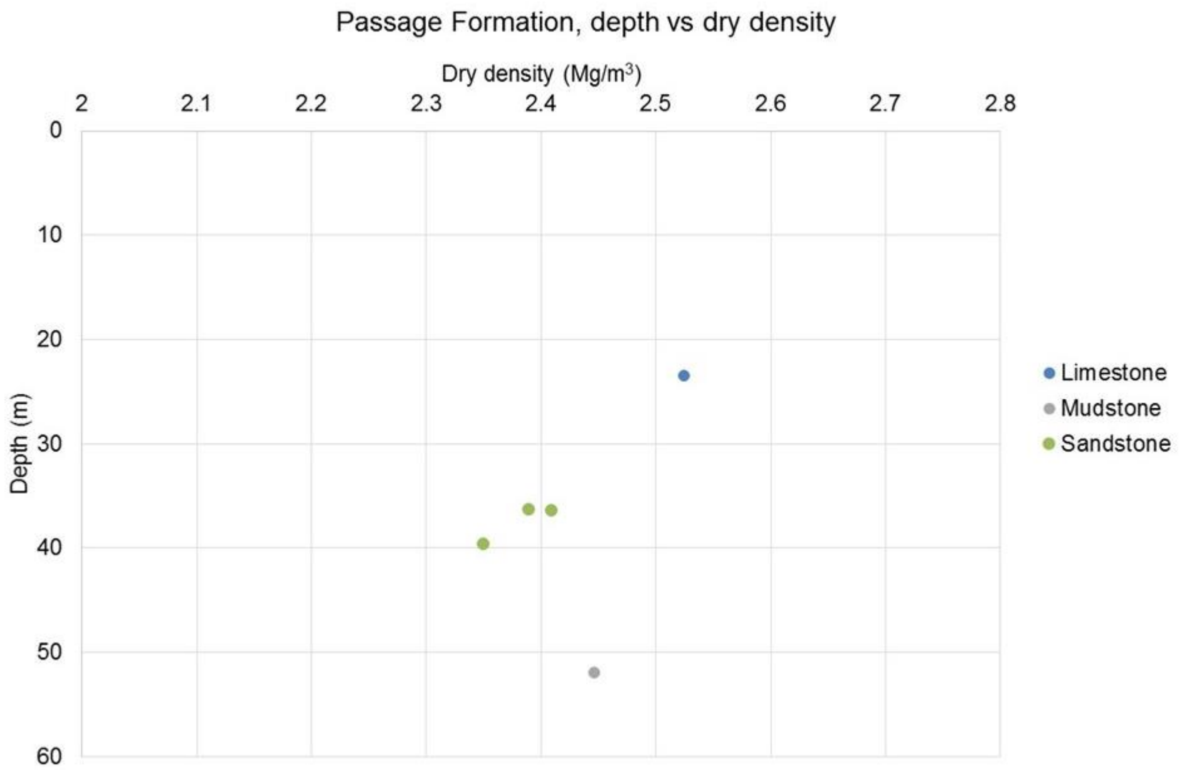


Figure 57. Passage Formation, the dry density at depth below ground level

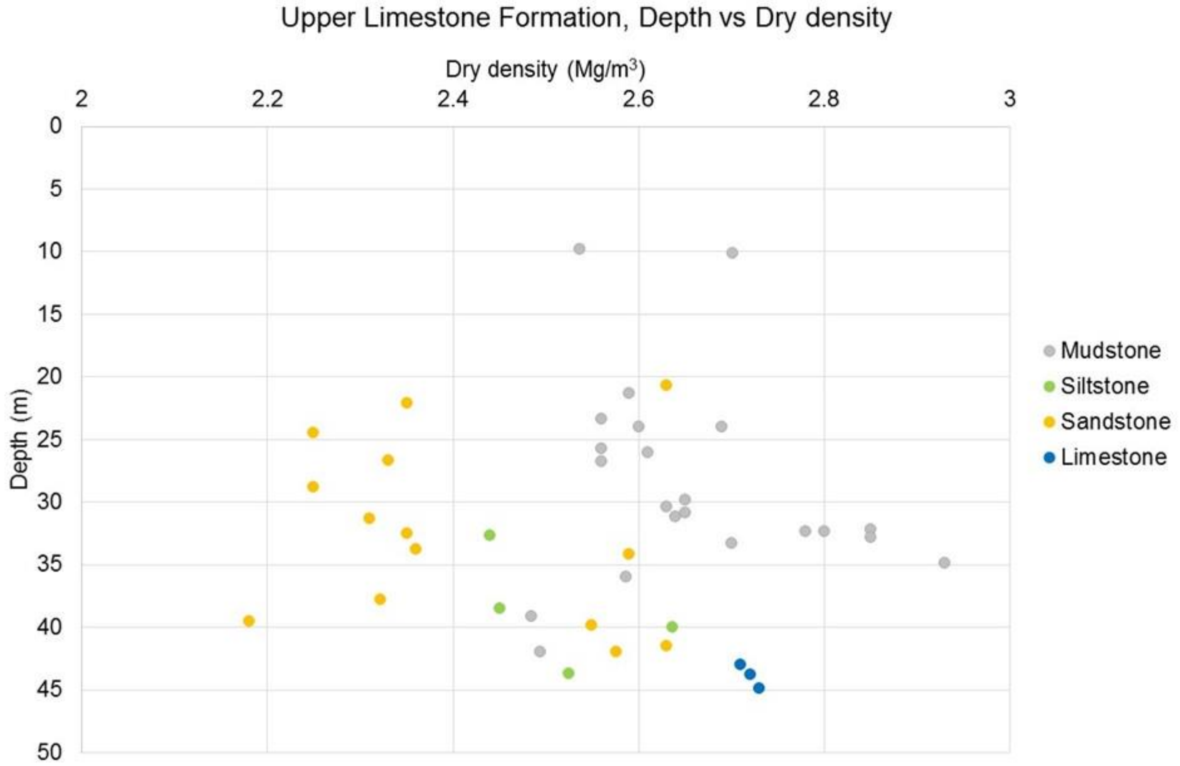


Figure 58. Upper Limestone Formation, the dry density at depth below ground level

The dry density vs porosity graph for all bedrock lithologies is in Figure 59.

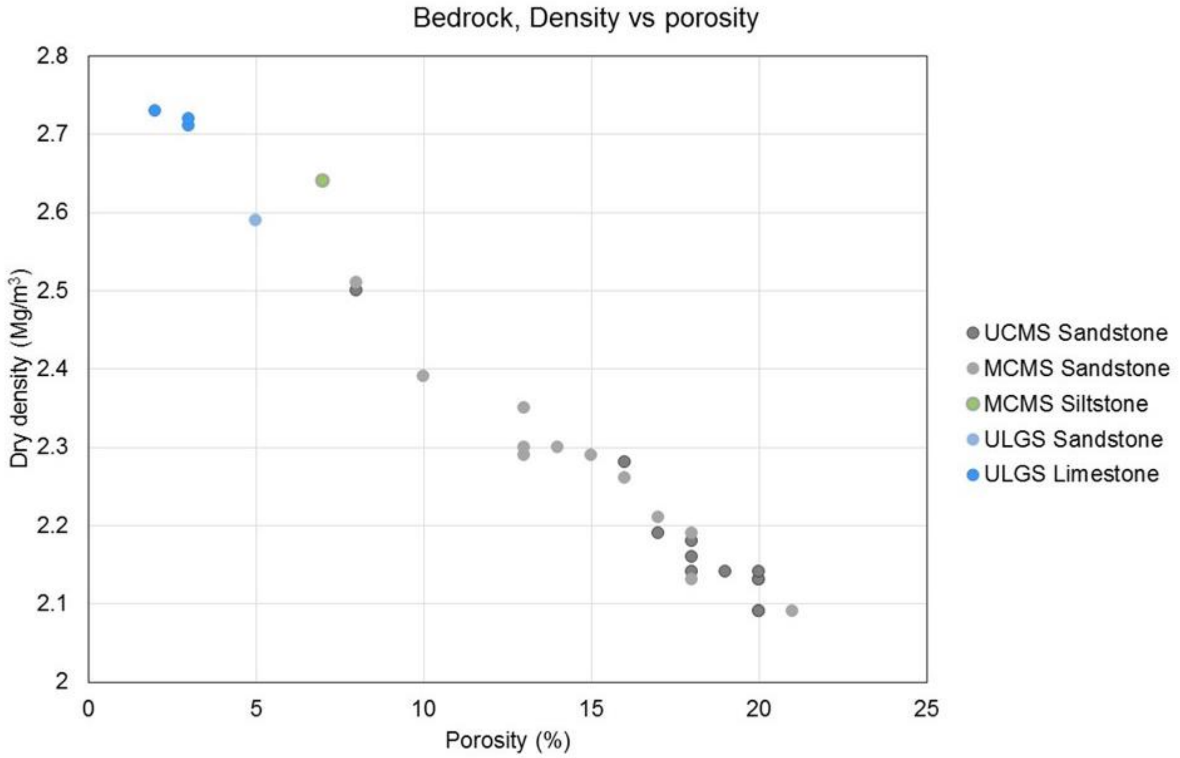


Figure 59. Porosity vs dry density for all bedrock units

There are insufficient data to calculate the relationship for siltstone or for limestone but the sandstones are assessed as in Figure 60. The regression line has an equation of:

$$\rho_d = 0.0318n + 2.7446 \qquad 3$$

r^2 of 0.9717 for 26 values

This equates to:

$n = -30.542\rho_d + 84.288$ 4

Equation 3 indicates a particle density (that is at zero porosity) of about 2.7446 Mg/m^3, which is higher than expected and as m = 0.0318 and the value of r^2 is not 1, this suggests that there is some variation in the value of particle density. However, equation 4 is used to calculate the value of porosity for sandstones only as shown in Figure 61.

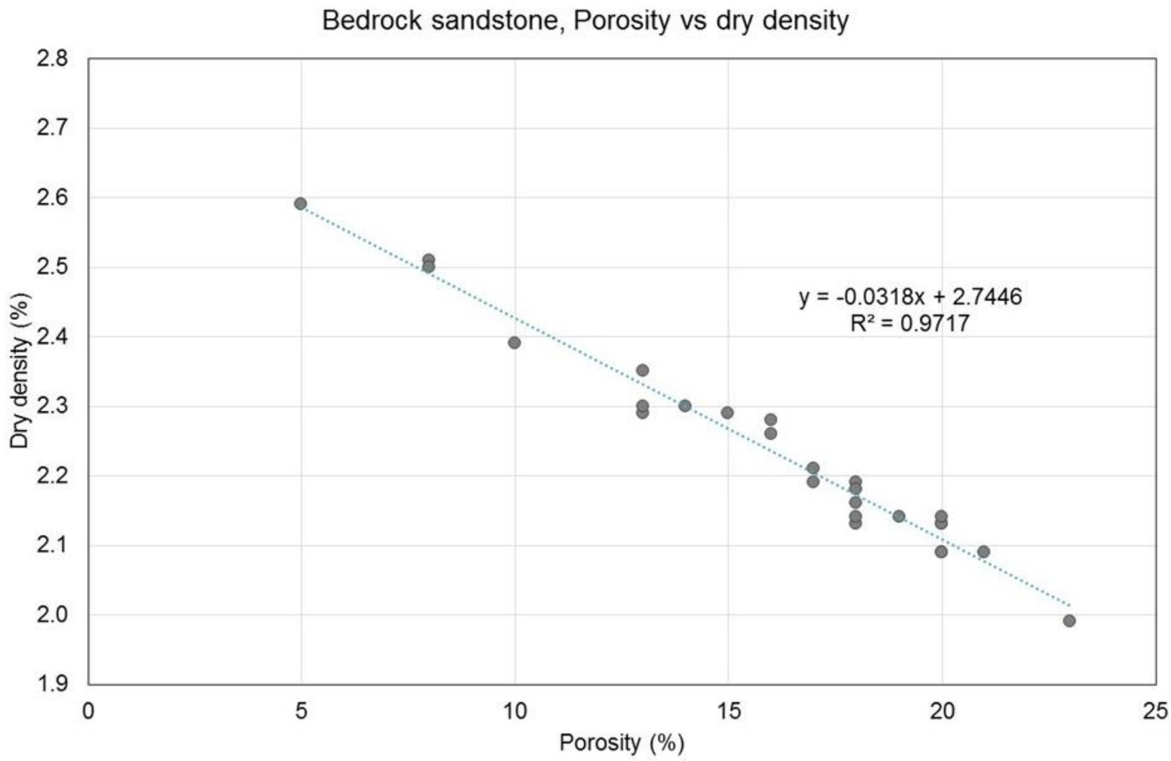


Figure 60. The porosity vs dry density for the sandstones with a linear regression line.

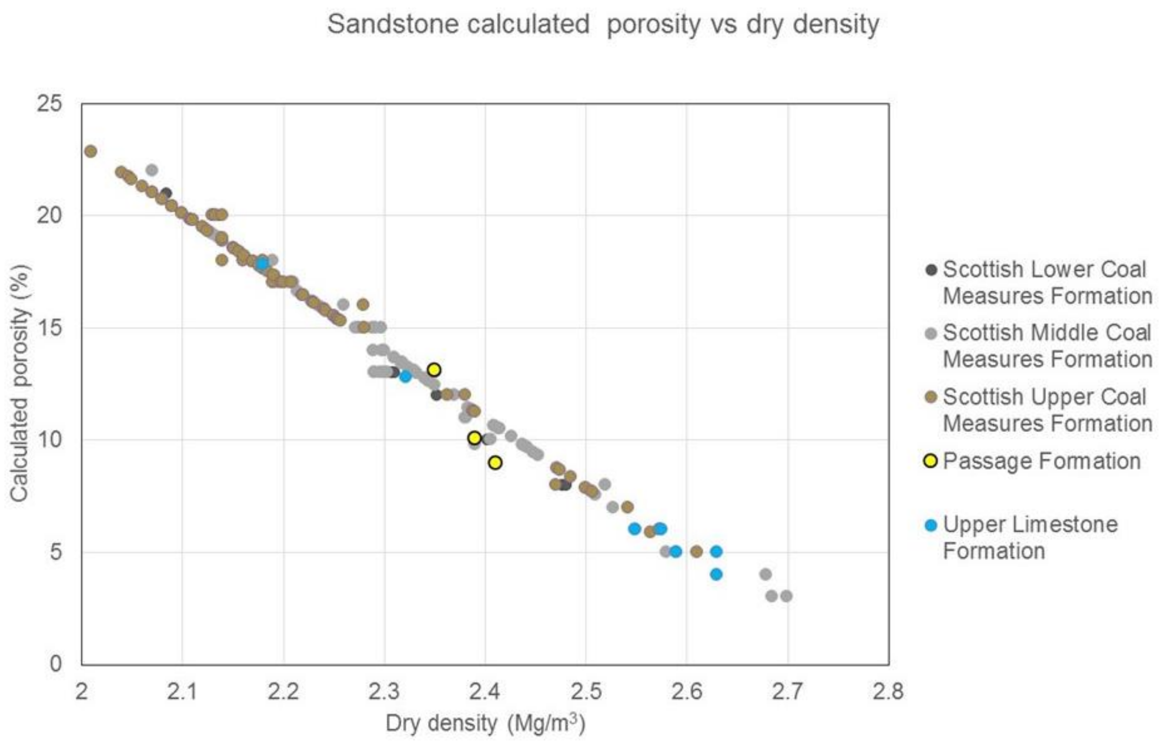


Figure 61. Dry density vs calculated porosity for sandstone.

Figure 62 shows the porosity (mostly calculated) with depth for each bedrock unit.

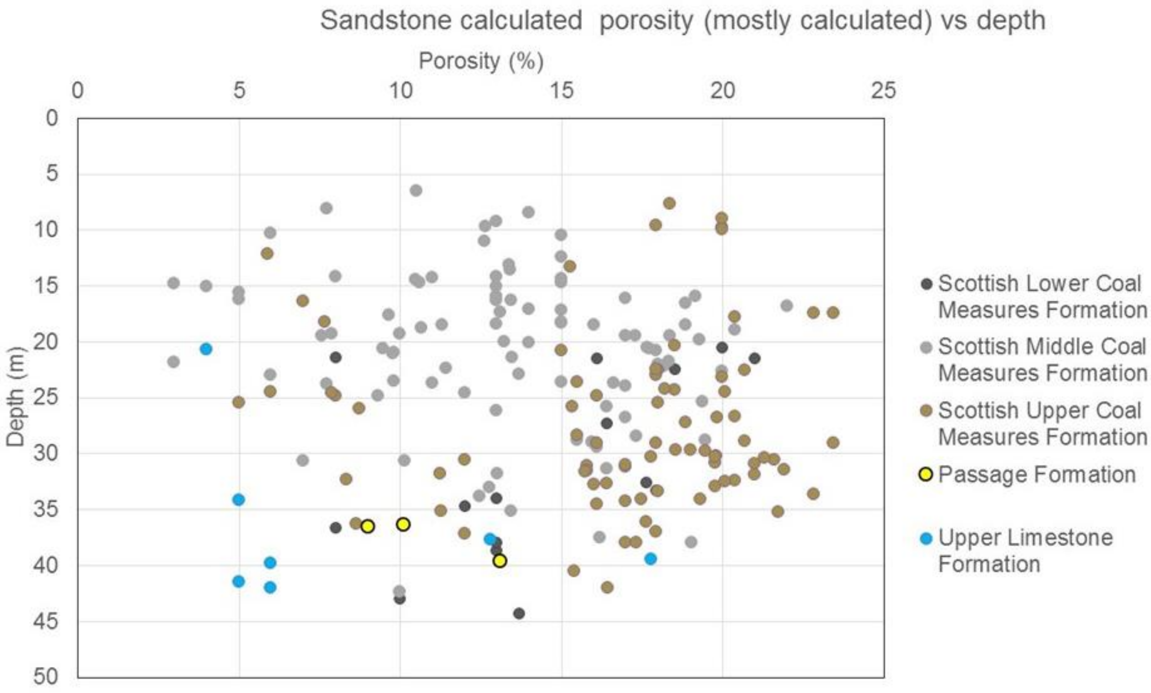


Figure 62. Depth vs porosity (mostly calculated) vs depth.

7.3 DISCONTINUITIES

Mechanical discontinuities identified in borehole core, which might increase rock mass permeability, are indicated in ground engineering in the description and by the fracture discontinuity state as fracture index, FI, (discontinuities per metre) or fracture spacing, I_f (mm). In the dataset for this area, fracture index is used more commonly. Rock quality designation (RQD), which is used in engineering rock mass assessment, can also be used. However, these data are all affected by the interpretation of the discontinuities by the logger as only natural discontinuities as in the ground should be included. Commonly, 'man-made' breaks, particularly along bedding planes, are included, generally, in error, and, although these can removed from the descriptions, breaks along bedding planes cannot be removed from the fracture state data. Fracture index values of 50 (20 mm or gravel sized) are given for material that is not intact, given as 99 in the database. The fracture index is plotted against depth for each unit in Figure 63 to Figure 67.

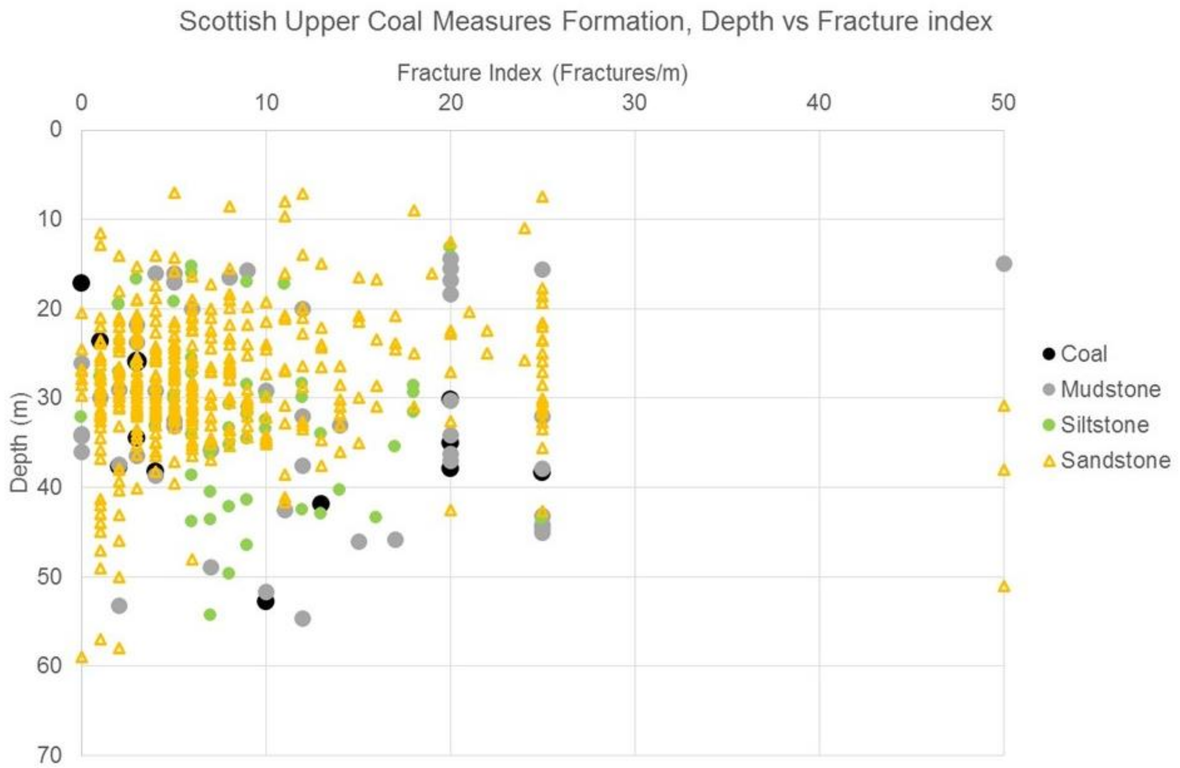


Figure 63. Scottish Upper Coal Measures Formation, depth vs fracture index

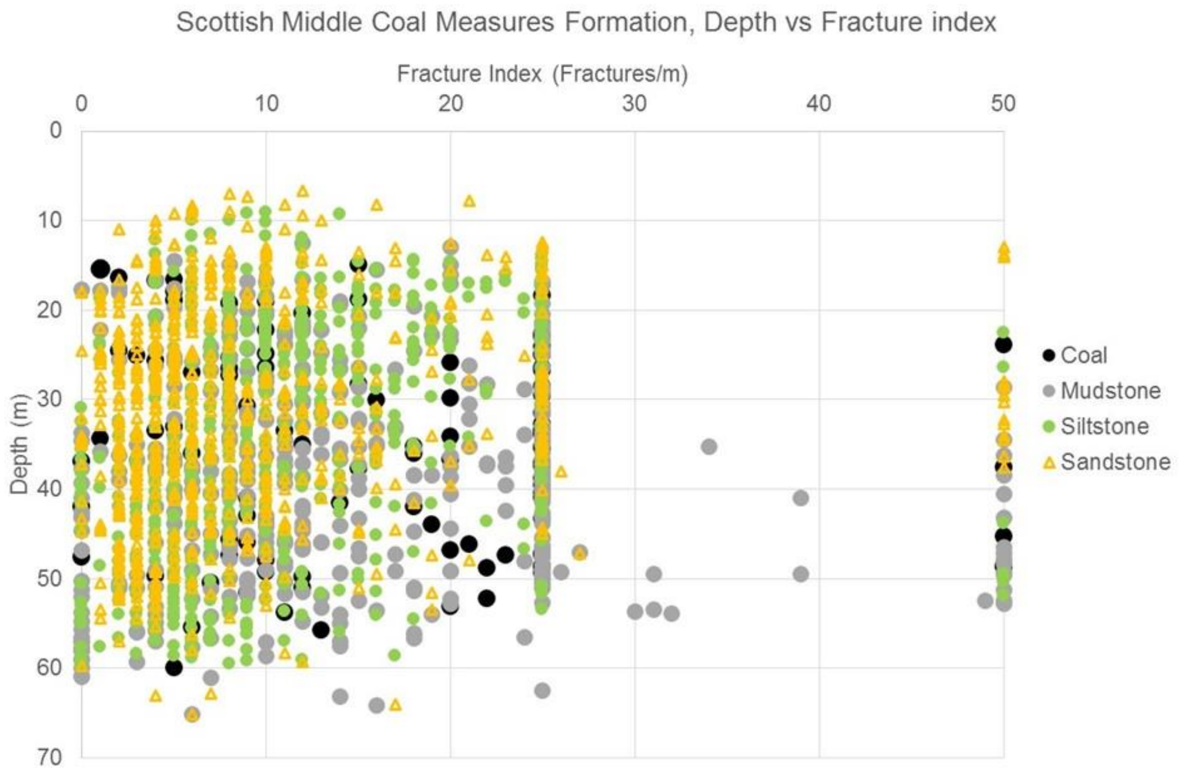


Figure 64. Scottish Middle Coal Measures Formation, depth vs fracture index

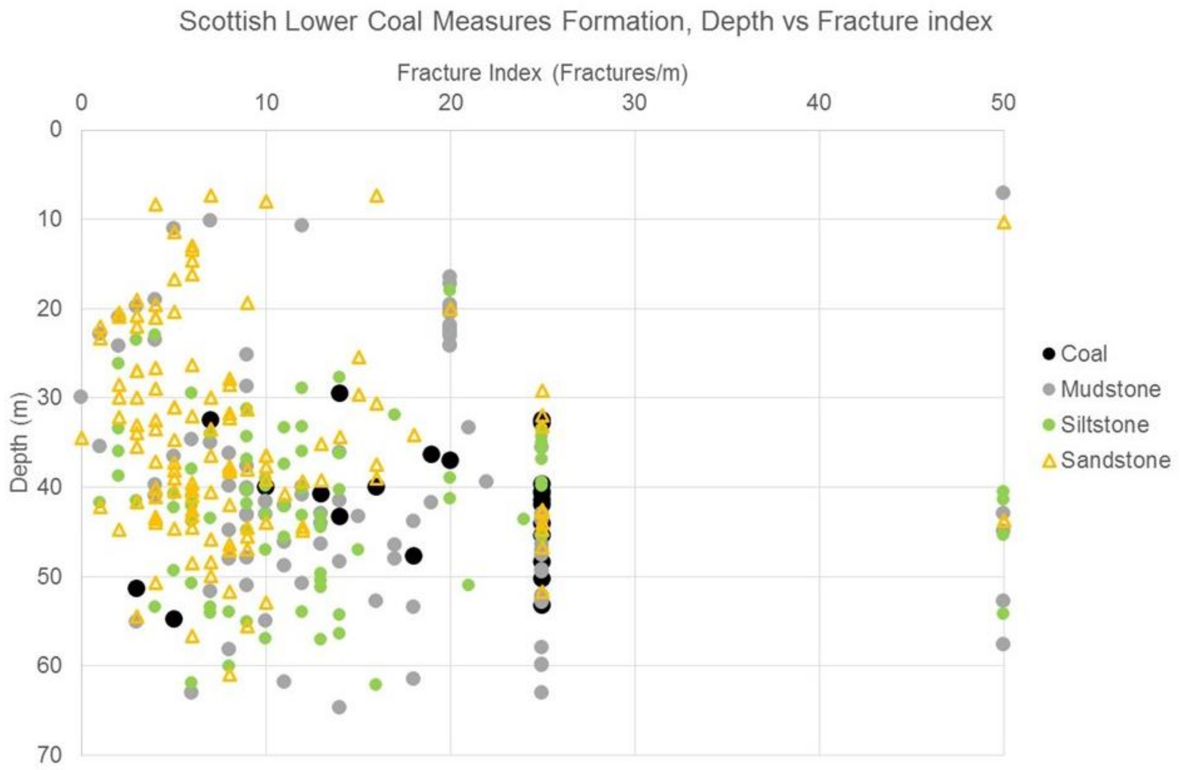


Figure 65. Scottish Lower Coal Measures Formation, depth vs fracture index

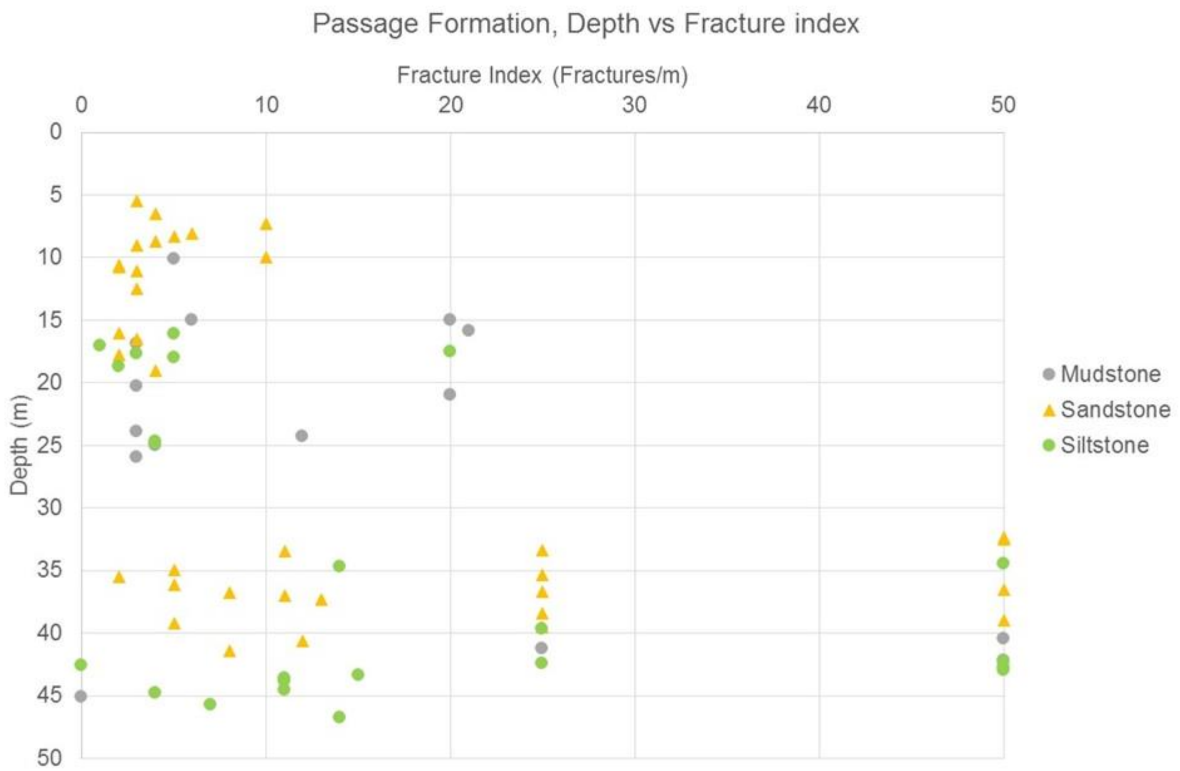


Figure 66. Passage Formation, depth vs fracture index

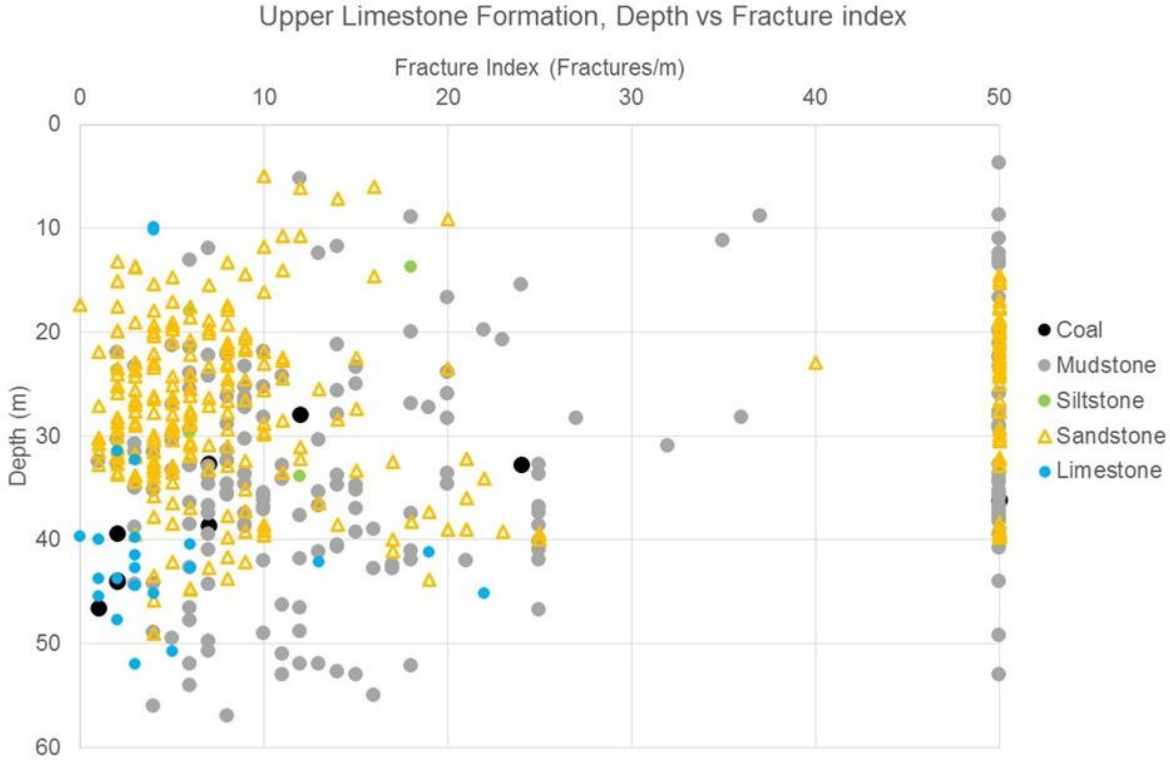


Figure 67. Upper Limestone Formation, depth vs fracture index

Further graphs of geotechnical data are given in Appendix 2.

8 Historical and recorded seismicity

This section contains a broad description of the seismicity in the British Isles and a detailed description of the seismicity around the Clyde Gateway area.

The UK lies on the north-west part of the Eurasian plate and at the north-east margin of the North Atlantic Ocean. The nearest plate boundary lies approximately 1500 km to the north-west at the Mid-Atlantic Ridge, where the formation of new oceanic crust at this divergent plate boundary results in significant earthquake activity. As a result of this geographic position, the UK is characterised by low levels of earthquake activity and correspondingly low seismic hazard.

The earthquake catalogue described here is based on the BGS UK earthquake database, which contains times, locations and magnitudes for earthquakes derived from both historical archives that contain references to felt earthquakes, and from instrumental recordings of more recent earthquakes.

The primary source of data for earthquakes before 1970 is the historical catalogue of Musson (1994), along with subsequent updates (e.g. Musson 2004, 2007). It contains earthquakes of moment magnitude of 4.5 Mw and above that occurred between 1700 and 1970, and earthquakes of 5.5 Mw and above that occurred before 1700. Each event has a location and magnitude determined from the spatial variation of macroseismic intensity, a qualitative measure of the strength of shaking of an earthquake determined from the felt effects on people, objects and buildings (e.g. Musson, 1996).

The primary sources of data from 1970 to present are the annual bulletins of earthquake activity published by BGS each year (e.g. Galloway et al., 2013). These contain locations and magnitudes determined from recordings of ground motion on a network of sensors in and around the UK (e.g. Baptie, 2012). The instrumental BGS database contains all events of 3.0 Mw and above, and some smaller earthquakes are well recorded by the UK seismic network.

Figure 68 shows a map of the UK seismicity. The symbols are scaled by magnitude (Mw). It is worth noting that the location uncertainty is ±5 km for instrumental earthquakes and up to ±30 km for historical earthquakes (Musson, 1994). The terranes (i.e. basement blocks bounded by faults (Bluck et al., 1992)), are homogeneous in terms of crustal properties (e.g. distribution and style of faulting), but the seismicity within each block is heterogeneous (Musson, 2007). There are spatial variations in the level of seismic activity across the UK. Western Scotland, western England, Wales, south-western Cornwall, and the area off the coast of the south-eastern England are the areas of highest activity. The eastern coast of Scotland, north-eastern England and Northern Ireland are almost earthquake-free (Figure 68).

The largest earthquake in the catalogue, and the largest known earthquake in the British Isles, is the 5.9 Mw 7 June 1931 event in the Dogger Bank area (Neilson et al., 1984). The largest instrumentally recorded onshore earthquake in the UK is the magnitude 5.1 Mw event on 19 July 1984 near Yr Eifel in the Lleyn Peninsula.

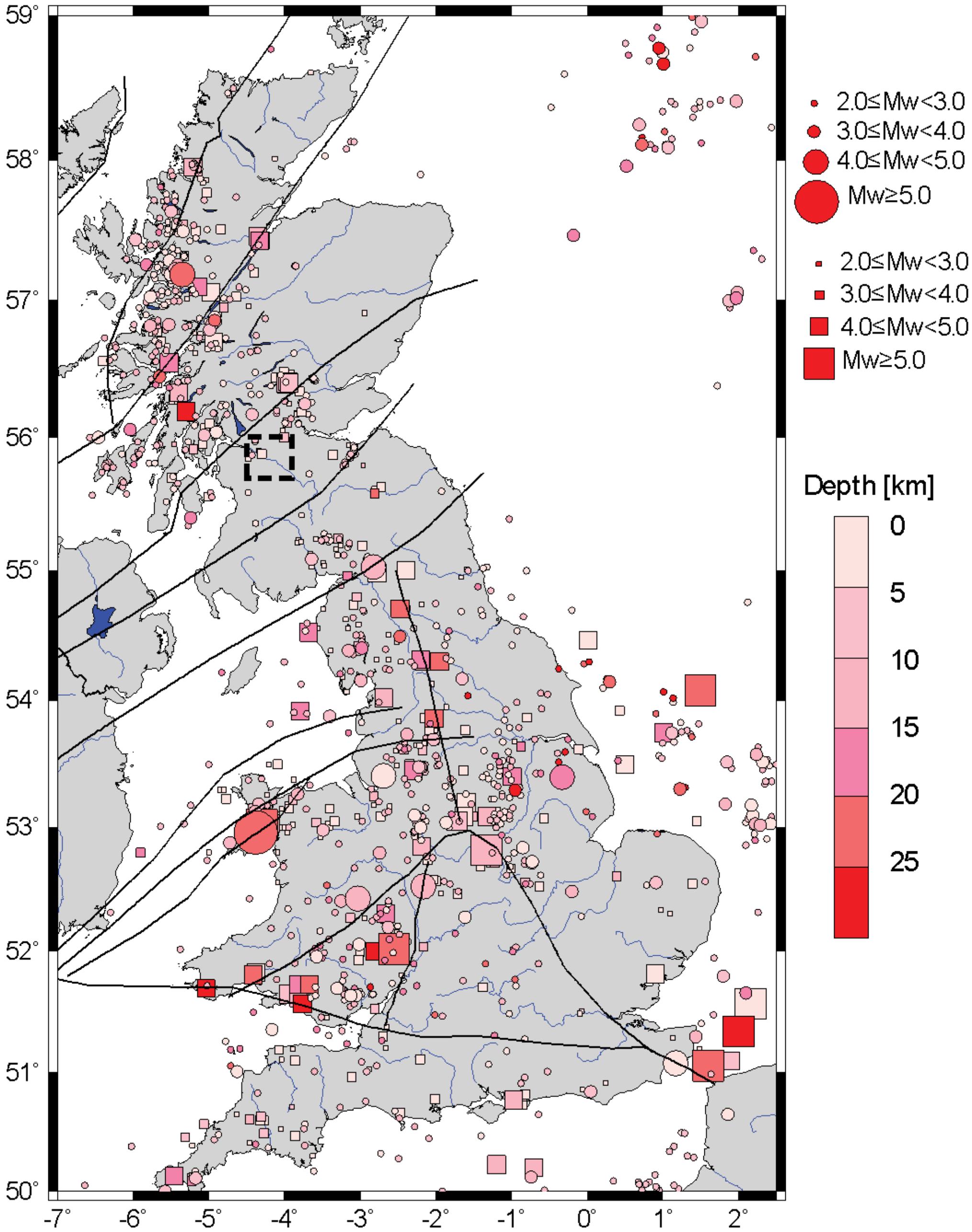


Figure 68 Distribution of earthquakes in the UK. Historical (pre-1970) and instrumental (post-1970) seismicity is indicated by squares and circles, respectively. Black lines are the simplified major faults (after Bluck, 1992). The dashed black square indicates the Clyde Gateway area.

8.1 REGIONAL PERSPECTIVE

To give a regional perspective, a wider study area is included in the rectangle between 49.9°N and 59°N latitude, and 8°W and 3°W longitude (Figure 69). This region is characterized by high levels of clustered seismicity with Mw ≤ 5 in the west coast of Scotland and low levels of seismicity with Mw ≤ 4 in the Midland Valley Terrane (Figure 69).

The largest earthquake recorded in Scotland was the 4.9 Mw 1880 Argyll event whose epicentre is around 80 km from the Clyde Gateway area. It was felt along the west coast of Scotland, east as far as Perthshire, throughout the Inner and Outer Hebrides, and in Northern Ireland (Musson 1989, 1994). The exact epicentre is uncertain. The most probable location is near Loch Awe, between Oban and Inveraray (Musson 1989, 1994). The extent of the felt area of this earthquake suggests that the focus was relatively deep (~ 25 km).

The seismicity in the Midland Valley Terrane is dominated by two earthquake swarms, one in Comrie and the other in the Ochil Hills (Figure 69). Earthquake swarms are defined as sequences of earthquakes clustered in time and space without a clear distinction of main shock and aftershocks. They are at a distance of ~66 km from the Clyde Gateway area. The Comrie swarms occurred in 1608, 1788–-1801 and 1839–1846 and are located just north of the Highland Boundary Fault, so may be related to activation of this structure. It can be questioned whether this activity is a swarm or consist of a mainshock with many fore- and after-shocks (Musson, 2007). The largest earthquakes in the Comrie swarms occurred in 1608 (4.3 Mw), 1801 (4.3 Mw), 1839 (4.5 Mw), and 1846 (4.1 Mw). The Ochil Hills swarms may be related to the Ochil fault that bounds the southern edge of the range of the hills (Musson, 2007). The activity consists of three discrete swarms, in 1736, in 1900–1916, and in 1979–1980, where the largest earthquakes were in 1736 (2.5 Mw), in 1905 and 1908 (2.9 Mw), in 1912 (3.4 Mw), and in 1979 (3.0 Mw).

The two largest events within 20 km of the Clyde Gateway area occurred on 14 December 1910 (3.1 Mw) and 16 July 1940 (3.4 Mw) (Figure 69). The epicentre of the 14 December 1910 Glasgow earthquake was in the north-west suburbs of Glasgow, in the Hillhead-Maryhill area. Superficial damage in the epicentral area included small cracks in plaster and dislodging of a few chimney pots. The earthquake was felt within the area bounded by Lochwinnoch, Dumbarton, Strathblane and East Kilbride, and probably also in Kilcreggan, Stirling and Dunblane (Gregory, 1911; Musson, 1994). The 16 July 1940 Kilsyth earthquake was felt in most of Midland Valley and in Strathspey (Musson et al., 1984, Musson, 1994). The only report of damage was the collapse of the gable wall of a house in Carronbridge (Musson, 1994). The area of the intensity map of the Kilsyth earthquake was similar to the intensity map of the 3.1 Mw 2 February 1940 Stirling event, whose epicentre was located to the north of the Kilsyth event (Musson, 1884, 1994).

There is no recorded seismicity within the the 5 km region from the Clyde Gateway area (the star in Figure 69).

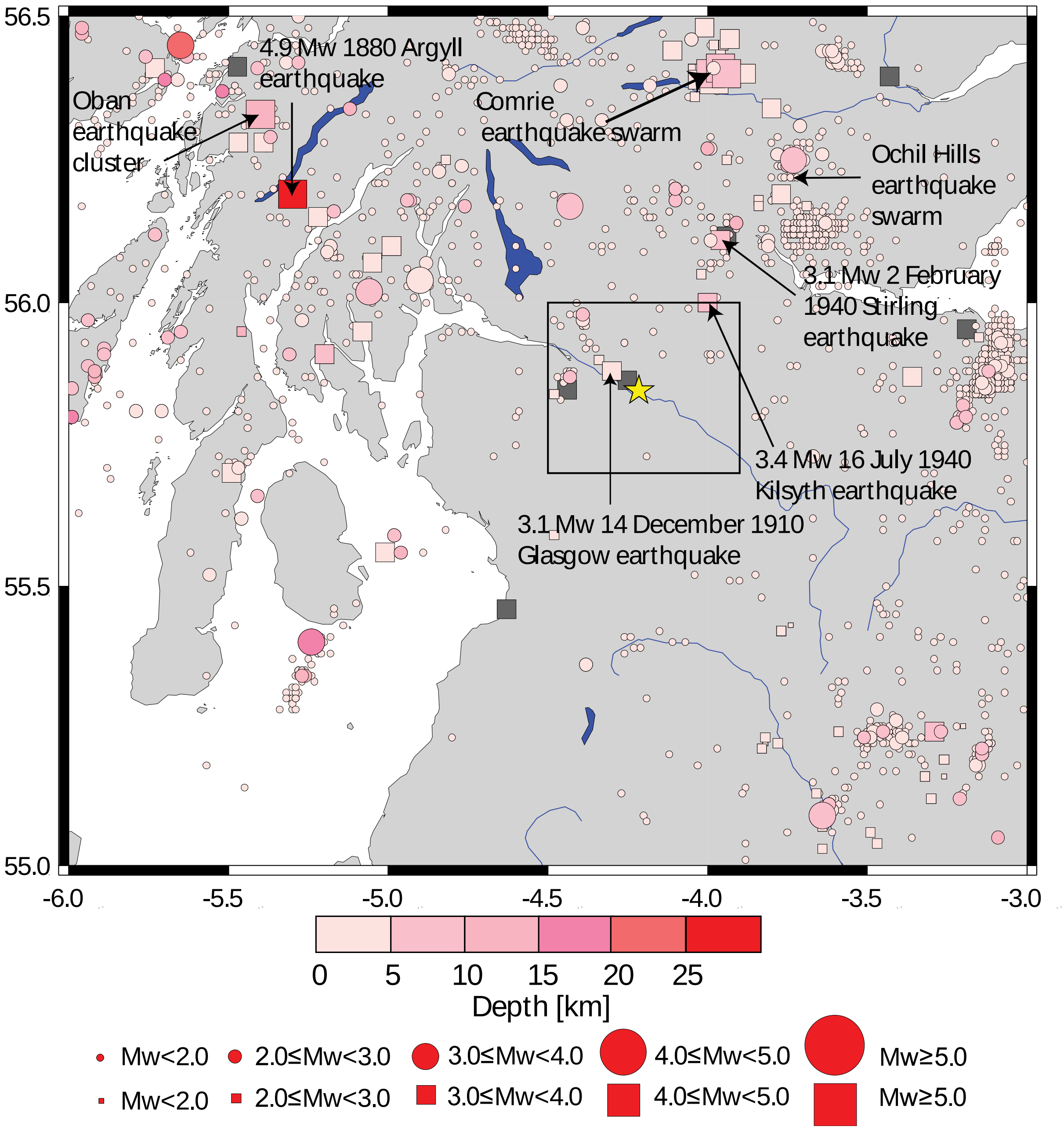


Figure 69 Historical (squares) and instrumental (circles) seismicity recorded in the study area. The symbols are scaled by magnitude and coloured by depth. The grey-shaded squares show towns and cities. The yellow star indicates the approximate Clyde Gateway area and the black square indicates the 20-km area around the area.

9 Remote sensed datasets

A summary of the availability of remote sensed (earth observation) data and the main uses of each data type relevant to the Clyde Gateway area is given below.

9.1 LANDSAT 8 OPTICAL AND THERMAL IMAGERY

The Landsat 8 satellite hosts

1) the OLI (Operational Land Imager), a satellite sensor that captures medium (30m) spatial resolution data in 9 spectral bands: 5 visible (VIS); 1 Near-infrared (NIR); 2 shortwave infrared (SWIR); and 1 Panchromatic (PAN) at higher (15 m) spatial resolution; and

2) the TIRS (Thermal Infrared Sensor) that captures data in 2 medium (100 m) spatial resolution Thermal Infrared (TIR) bands.

The data are used to continuously, systematically and consistently assess changes in Earth's landscape, study and monitor landmasses, and create a historical archive of spectral information from the Earth's surface for use in agriculture, geology, forestry, regional planning, education, mapping, and global change, characterisation of urban growth, emergency response and disaster relief. Landsat 8 (2013-present) is the continuity mission for Landsat 7 (Enhanced Thematic Mapper Plus), which was launched in 1999 but developed sensor technical issues in 2003.

- Landsat 8 imagery is free and there are established processing algorithms
- Accessible through http://earthexplorer.usgs.gov
- No limitations in redistribution of BGS-processed imagery, with acknowledgement to USGS
- 16-day repeat with 2 potential images from Path/Row: 205/021 and 206/021
- Some limited cloud-free images are available for the Clyde Gateway area
- LC8: Path 205 / Row 21: 25/10/2016; 28/02/2016; 05/11/2014; 04/12/2013
- LC8: Path 206 / Row 21: 01/11/2016; 09/05/2016; 23/07/2014; 18/04/2014; 20/07/2013

9.2 ASTER OPTICAL AND THERMAL IMAGERY

ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) is a satellite sensor that captures high spatial resolution data in 14 spectral bands, including 3 bands in Visible and Near Infrared (VNIR) at 15 m, 6 bands in Shortwave Infrared (SWIR) at 30 m and 5 bands in Thermal Infrared (TIR) at 90 m; it also provides stereo viewing capability for digital elevation model creation. ASTER data is used to obtain detailed maps of land surface temperature, reflectance and elevation, and to observe, understand, and model the recent changes of the Earth system. It has applications for topographic mapping, land-use/cover mapping, monitoring surface/land temperature, emissivity, reflectance and elevation changes. ASTER was launched in 1999 but developed a technical fault with SWIR data in 2008.

- ASTER data are free and there are established processing algorithms
- Accessible through http://reverb.echo.nasa.gov
- No limitations in redistribution of BGS-processed imagery, with acknowledgement to NASA
- Some limited cloud-free images are available over the Clyde Gateway area
- 25/08/2000 - AST_L1B_003_20000825115426.hdf
- 01/05/2001 - AST_L1B_003_20010501114324.hdf
- 31/03/2007 - AST_L1B_003_20070331113344.hdf

9.3 HIGH SPATIAL RESOLUTION OPTICAL SATELLITE IMAGERY

There are a number of satellite platforms that acquire high spatial resolution optical imagery at visible, near-infrared and shortwave infrared wavelengths. Current platforms are WorldView-1 (2007-present), GeoEye-1 (2008-present), WorldView-2 (2009-present), Pleiades (2011-present), SkySat-1 (2013-present), WorldView-3 (2014-present), SkySat-2 (2014-present), WorldView-4/GeoEye-2 (2016-present) as well as decomissioned QuickBird-2 (2002-2015), IKONOS (1999-2015) can provide sub-metre to metre spatial resolution in a few spectral bands. In addition there is SPOT-6 (2012-present) and SPOT-7 (2014-present) that can provide near-metre spatial resolution in a few spectral bands. Images are used to observe, understand, and model the recent changes of the Earth system and have applications for land-use/cover mapping for agriculture, geology, forestry, regional planning, education, mapping, and global change, characterisation of urban growth, emergency response and disaster relief.

- These high spatial resolution datasets can be expensive and have to be purchased through a reseller (i.e. Airbus, DigitalGlobe)

- Some cloud-free images are available over the Clyde Gateway area
- BGS is unlikely to be able to redistribute raw imagery, but some potential for processed images

9.4 HIGH SPECTRAL AND SPATIAL RESOLUTION OPTICAL AIRBORNE IMAGERY

NERC owns an airborne platform that can be used to acquire high spatial and spectral resolution visible and near-infrared (VNIR), shortwave infrared (SWIR) and thermal infrared (TIR) imagery using specialist airplane-mountable hyperspectral sensors. The AisaEAGLE (VNIR), AisaHAWK (SWIR), AisaFENIX (VNIR-SWIR) and AisaOWL (TIR) can be mounted in conjunction with a digital Leica photogrammetric format survey camera, the latter can be used to generate high resolution DEM, although it is more common to acquire LiDAR data at the same time (see later). The imagery can be used to investigate geoscience and environmental issues of the ground surface imaged during the survey. In order for a survey to be performed by NERC, an announcement of opportunity is opened to the science community and a science case must be written and submitted for peer-review. These targeted opportunities do not necessarily mean that the data will be acquired due to constraints and matching of weather conditions and surface conditions specified in the science case.

There have been no NERC surveys flown so far over the Clyde Gateway area.

9.5 SAR

Synthetic Aperture Radar (SAR) is an active system that transmits a beam of electromagnetic energy in the microwave region towards the ground surface and measures the backscattered response. SAR does not require solar reflected radiation or thermal emitted radiation for measurement and therefore can provide both day and night imagery of the Earth. SAR measurements are also relatively unaffected by cloud, fog or precipitation so the ground surface can be imaged independent of adverse weather conditions. SAR imagery can be used to monitor changes in the land surface through surface cover and ground motion, in addition to providing emergency mapping support in the event of natural disasters. SAR imagery has been acquired by a multitude of systems ERS-1 SAR (1991–2000), ERS-2 SAR (1995–2011), Envisat ASAR (2002–2012), Cosmo-SkyMed (2010-present), Radarsat-2 (2007–), TerraSAR-X (2007–present), TanDEM-X (2010–present) and Sentinel-1 (2014 and 2016–present). Data can be looked at as a single time-slice image or in combination with other temporal images of the same surface area to determine millimetric-precision vertical ground motion using established Interferometric (i.e. PSInSAR, IPTA and ISBAS) techniques.

- High resolution radar data can be expensive, but Sentinel-1 data are free
- The ESA Sentinel Toolbox can be used to process the Sentinel-1A and 1B data, which is accessible through https://scihub.copernicus.eu/dhus
- Nigel Press Associates (became Fugro, now CGG) were paid to process SAR imagery for ground motion of Glasgow about 14.5 years ago. BGS holds a copy of these data, probably ERS-1/-2 data with/out ENVISAT ASAR, in its archives (conditions of use require to be clarified). The area was fairly stable during that period of monitoring.
- BGS staff have extensive expertise and technical background in processing satellite-borne radar data for ground motion using detailed GAMMA UNIX-based software. The only BGS software installation is node-locked in BGS Keyworth..
- Dr. Zhenhong Li (Newcastle Uni, ex-Glasgow Uni) processed some SAR data of Glasgow and there is a PhD student (J.Stockamp) researching ground motion including on the Glasgow area.

10 Conclusions: Implications for planning of a geothermal research facility

10.1 GAP ANALYSIS

A great deal of legacy shallow borehole data (less than 50 m) and mine abandonment plan data are available for the Clyde Gateway area, as well as existing baseline datasets for monitoring (e.g. BGS systematic geochemistry, hydrogeological monitoring in superficial deposits) . However, some clear data gaps are apparent from the summary of diverse data sources currently available to BGS as described in this report (Table 22). The most critical gaps at this planning stage for the Glasgow Geothermal Energy Research Field Site (GGERFS) are:

- Borehole, geophysical well log and seismic data to define the bedrock lithology and fault structure at depths greater than a few hundred metres, *leading to* uncertainty for deep borehole prognosis and understanding of deep fault structure
- Bedrock hydrogeology data, temperature and hydrogeochemistry data within or close to the area of interest *leading to* uncertainty in any geothermal modelling and planning for monitoring

Type	Data gap	Implication	Mitigation	New data collection would involve
Bedrock geology	Lack of borehole, mining data at greater depths than 435 m	Uncertainty for planning of boreholes >435 m in depth	Use surrounding geology, boreholes, wells	New 'deep' borehole
Faults	Lack of seismic data to define fault geometry at depth	Uncertainty for planning of boreholes > 435m in depth	Mine plan data characterises faults at <300 m. Seismic from nearby gives indication of fault geometries	New 'deep' borehole, new seismic reflection data. ?Other geophysical techniques
Rock properties	Rock property data (e.g. porosity, permeability, temperature very sparse at depths greater than a few hundred metres)	Borehole and geothermal productivity planning difficult	Use data from comparable depths /stratigraphy from across Midland Valley of Scotland	New 'deep' borehole testing and sample analysis
Hydrogeol ogy	Lack of bedrock monitoring boreholes	Lack of data on groundwater levels, chemistry, temperature through time	Talk to Councils and SEPA	New characterisation boreholes and adoption of existing boreholes
Site specific geophysic al datasets	No BGS data currently located	Techniques could provide a range of interpretations, primarily on shallow subsurface	Further BGS, Council etc requests if appropriate	

Table 22 Examples of main data gaps identified

BGS knowledge gaps: BGS has extensive data holdings, information and knowledge to define a geological platform for the Clyde Gateway area. Much of that knowledge is systematic and regional as opposed to local and site specific. BGS is strongly aware that input of data and knowledge from stakeholders (academic, Government and local Government, industry, local people) are required, where they bring both specialist and local expertise. Examples of this include aspects of research into geothermal energy from mine waters, the site specific knowledge of Local Authorities, site investigation contractors, consultants, etc. Stakeholder input will therefore form important next steps in development of GGGERFS in the Clyde Gateway area.

10.2 SCIENCE QUESTIONS REVISITED

As a result of gathering BGS data and knowledge concerning the geological platform for the Clyde Gateway area, some detail has been added to the initial science questions described in section 1.4. A vision statement for GGERFS has also been prepared (Appendix 3).

*Minewater geothermal*The research will be built around the measuring and monitoring of minewater flow in a complex system of multiple mined seams, which in turn lie within a complex, faulted succession:

- Do faults act as barriers or conduits for flow?
- How far does pumping/heat extraction at one site influence heat and fluid flow at another site?
- What are the hydrogeological characteristics and impacts of mine workings of different styles/ages (e.g. longwall vs stoop and room); and what is the interaction between these and the surrounding un-mined aquifer.
- What are the controls of temperature distribution through mine workings?
  This will require the identification of patterns of recharge, fluid flow pathways, conduction and convection processes, and thermal breakthrough through detailed assessment of all hydrogeological and mine dewatering information, and additional borehole and outflow measurements. coupled with modelling of the flow system.
- What volume/percentage of the groundwater and/or mine waters can be abstracted and returned annually without affecting long term heat transfer?
- Can we predict if, and over what timeframe, there will be thermal breakthrough from returning cold water to mines?

Hot sedimentary aquifer geothermal

- Are sandstone aquifers: hot enough; permeable enough; and have enough volume for continued geothermal supply?
- What are the roles of: mudstones etc and other seals in compartmentalising the resource and influence on resource potential; and of faults and other discontinuities as barriers of, or conduits to, flow.

General

- What monitoring is required to address complexities of the geothermal gradient in a substantially anthropogenically-influenced groundwater environment
- What potential is there, and on what scales, for the subsurface storage of heat and transfer of heat
- What is the potential for linkage(s) of any strategic heat resource (heating, cooling, heat storage) to a developing District Heating Network

Identified Data gaps

- Aquifer hydraulic properties – transmissivity, permeability, storativity; flow types
- Key groundwater flow pathways and connectivity – through the unmined and mined Carboniferous aquifer; between Quaternary and Carboniferous aquifers; through and related to artificial ground; different recharge sources.
- Groundwater flow rates
- Hydrogeological properties of faults and fault zones
- Constraints on the geothermal gradient in non-mined areas, and identify how the geothermal gradient is altered through mining; understand possible impacts of pumping (therefore recharge rates and system sustainability, changing temperatures)
- Heat flow measurements to depth via multi-depth equilibrium temperature measurements and conductivity measurements from core or chippings. This would improve the heat flow data set for

Scotland and improve estimations, including an understanding of the conducting/insulating behaviour of certain formations such as the bulk behaviour of the Scottish Coal Measures Group

- Data to investigate the hypothesis that the high heat flow beneath Glasgow is due to groundwater upwelling
- Data to understand the impacts of stratigraphical and faulted surfaces on temperature distributions

Appendix 1 BGS Geochemical Maps of the Clyde Gateway Area Surface Environment (from samples collected in 2001, 2003 and 2011)

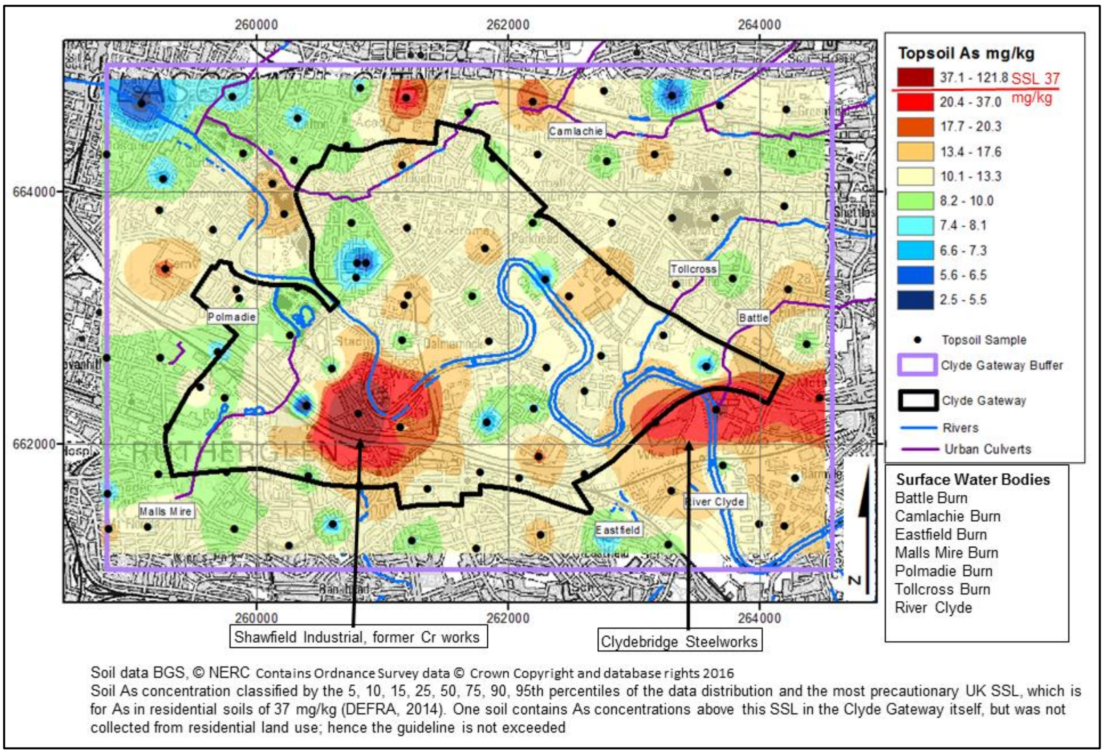


Figure 70 Total arsenic concentration in topsoil across the Clyde Gateway area collected in 2001 and 2011. Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2017. Licence number 100021290 EUL

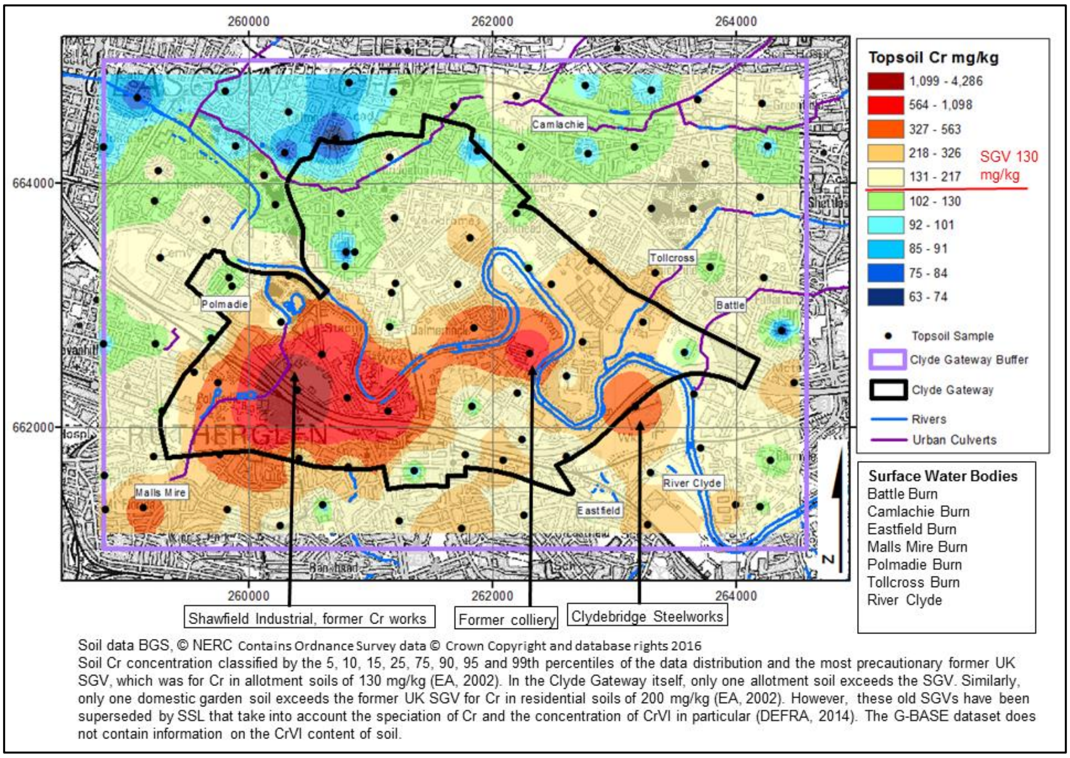
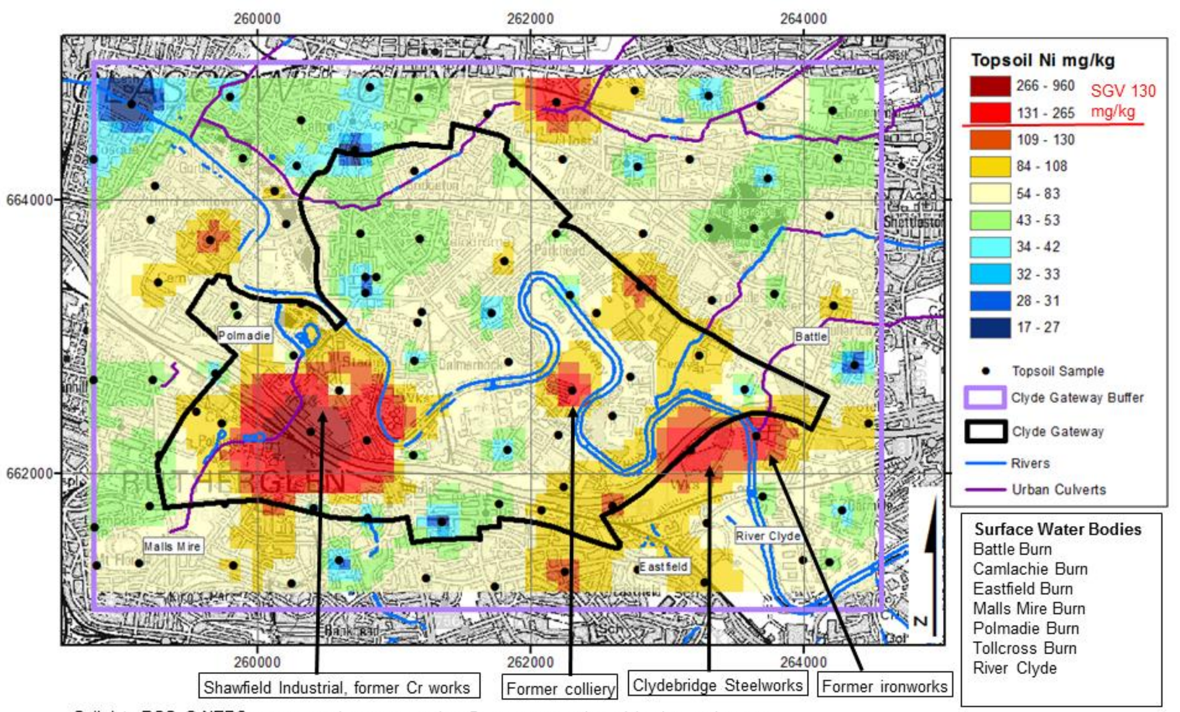
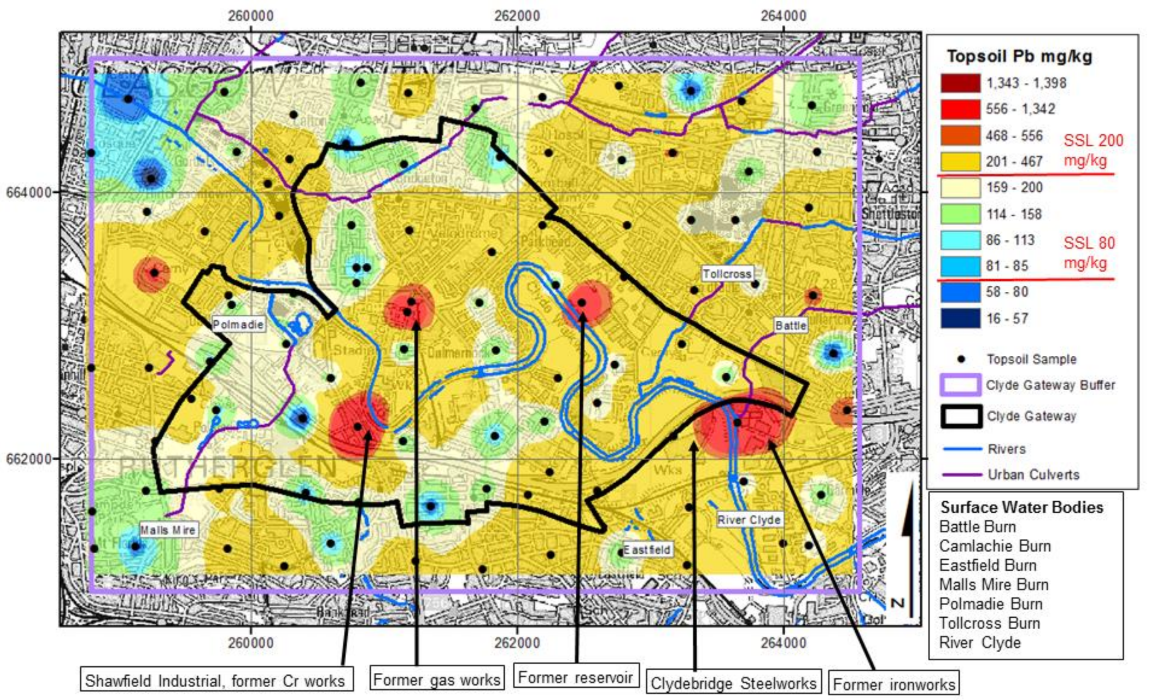


Figure 71 Total chromium concentration in topsoil across the Clyde Gateway area collected in 2001 and 2011. Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2017. Licence number 100021290 EUL



Soil data BGS, © NERC Contains Ordnance Survey data © Crown Copyright and database rights 2016
Soil Ni concentration classified by the 5, 10, 15, 25, 50, 75, 90 and 99th percentiles of the data distribution and the most precautionary UK SGV, which is for Ni in domestic garden soils of 130 mg/kg (EA, 2009). Six soils contain Ni concentrations above this SGV, however, none were collected from residential land use; hence the guideline is not exceeded

Figure 72 Total nickel concentration in topsoil across the Clyde Gateway area collected in 2001 and 2011. Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2017. Licence number 100021290 EUL



Soil data BGS, © NERC Contains Ordnance Survey data © Crown Copyright and database rights 2016
Soil Pb concentration classified by the 5, 15, 25, 50, 75, 95 and 99th percentiles of the data distribution and the UK SSL for allotment (80 mg/kg) and residential (200 mg/kg) soils (DEFRA, 2014). Within the Clyde Gateway itself, two allotment soils exceed the allotment SSL and two residential soils exceed the residential SSL. However, since only one soil sample was collected at each location, further investigations would be required to quantify soil quality in these specific areas.

Figure 73 Total lead concentration in topsoil across the Clyde Gateway area collected in 2001 and 2011. Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2017. Licence number 100021290 EUL

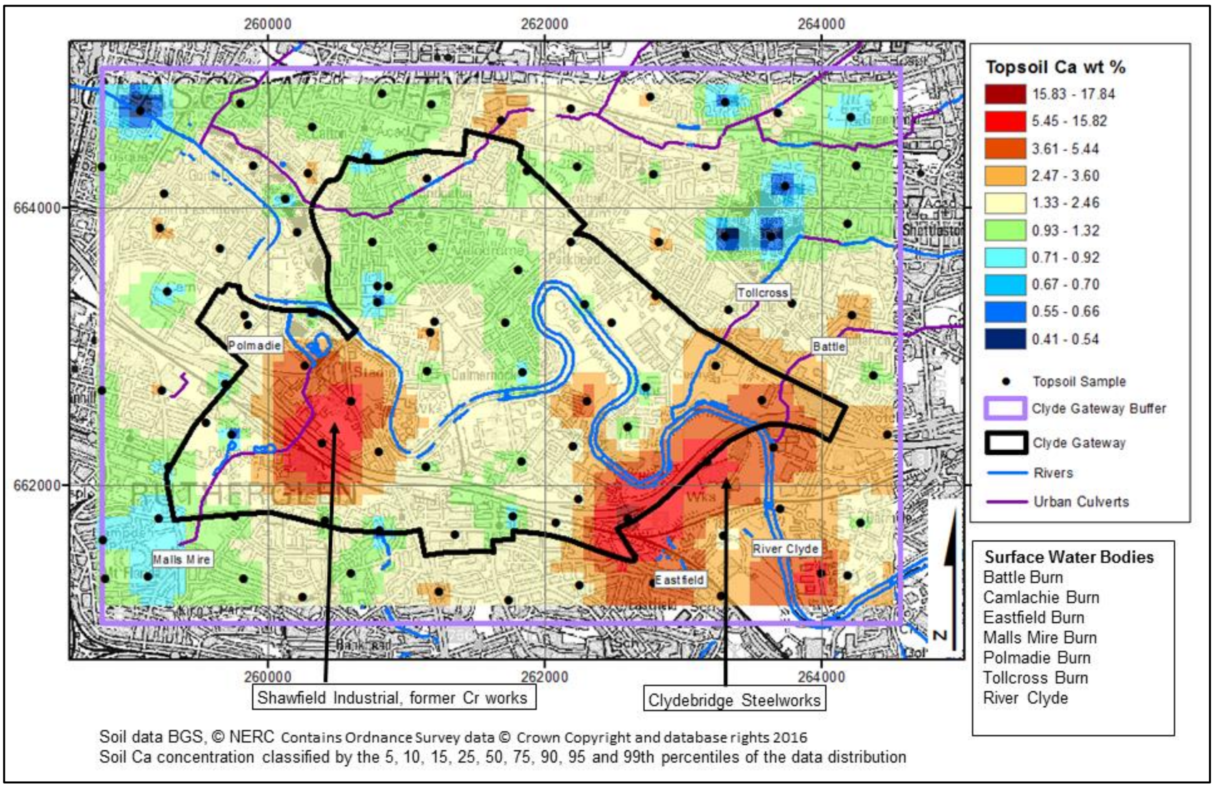


Figure 74 Total calcium concentration in topsoil across the Clyde Gateway area collected in 2001 and 2011. Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2017. Licence number 100021290 EUL

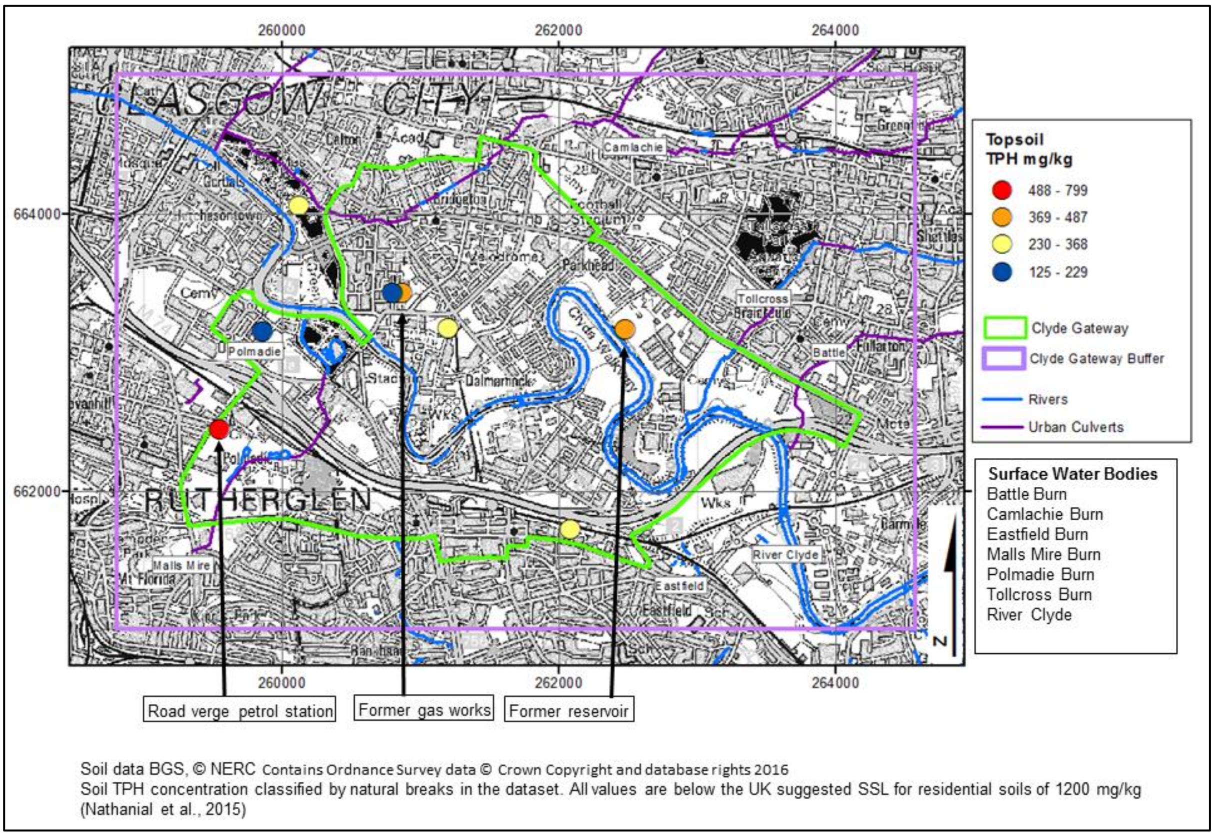


Figure 75 Total petroleum hydrocarbon (TPH) concentration in topsoil across the Clyde Gateway area collected in 2011. Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2017. Licence number 100021290 EUL

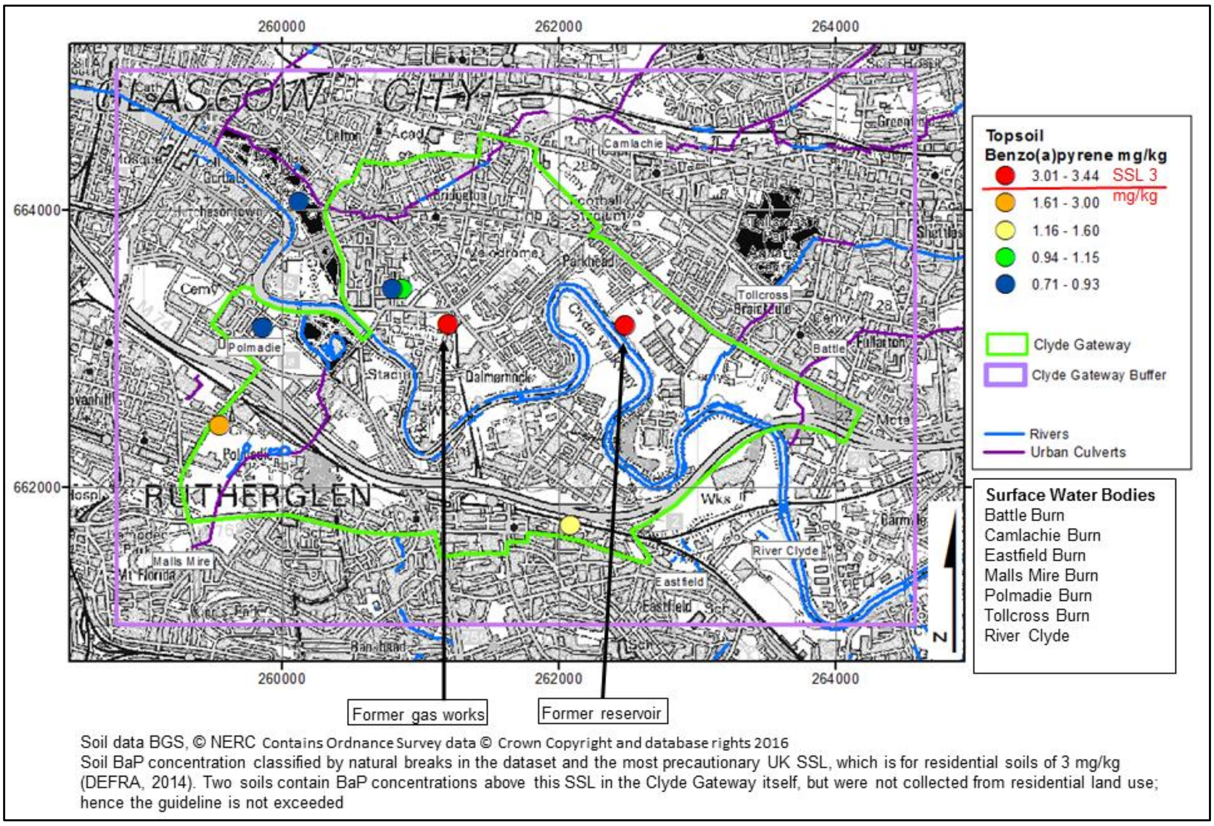


Figure 76 Benzo(a)pyrene (BaP) concentration in topsoil across the Clyde Gateway area collected in 2011. Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2017. Licence number 100021290 EUL

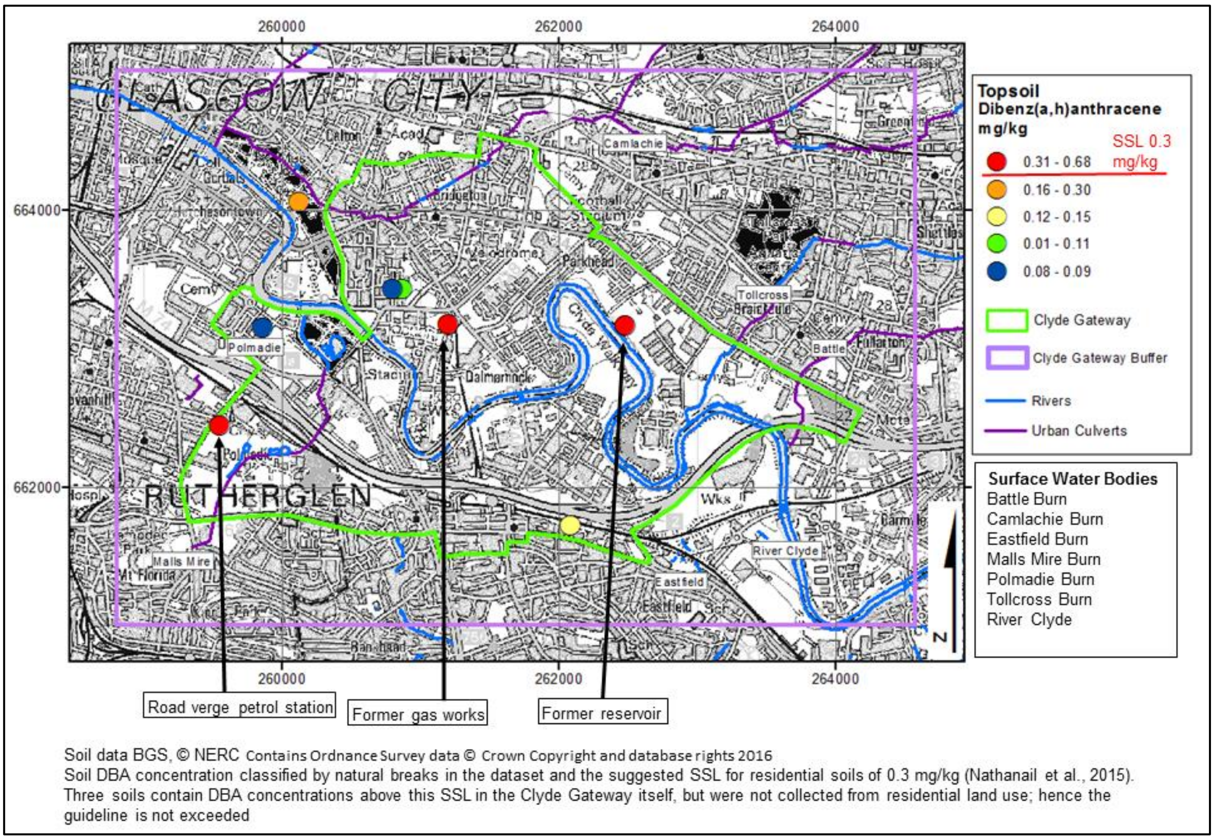


Figure 77 Dibenz(a,h)anthracene (DAB) concentration in topsoil across the Clyde Gateway area collected in 2011. Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2017. Licence number 100021290 EUL.

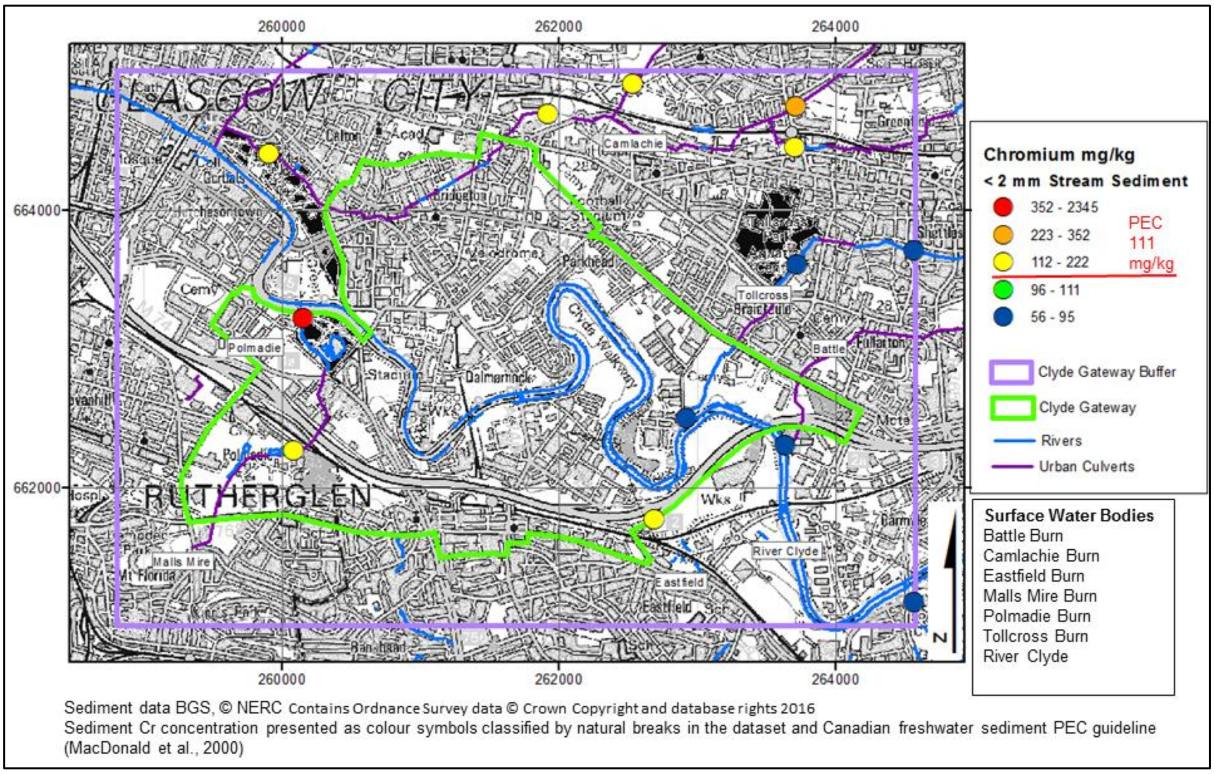


Figure 78 Total chromium concentration in stream sediment across the Clyde Gateway area collected in 2003. Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2017. Licence number 100021290 EUL

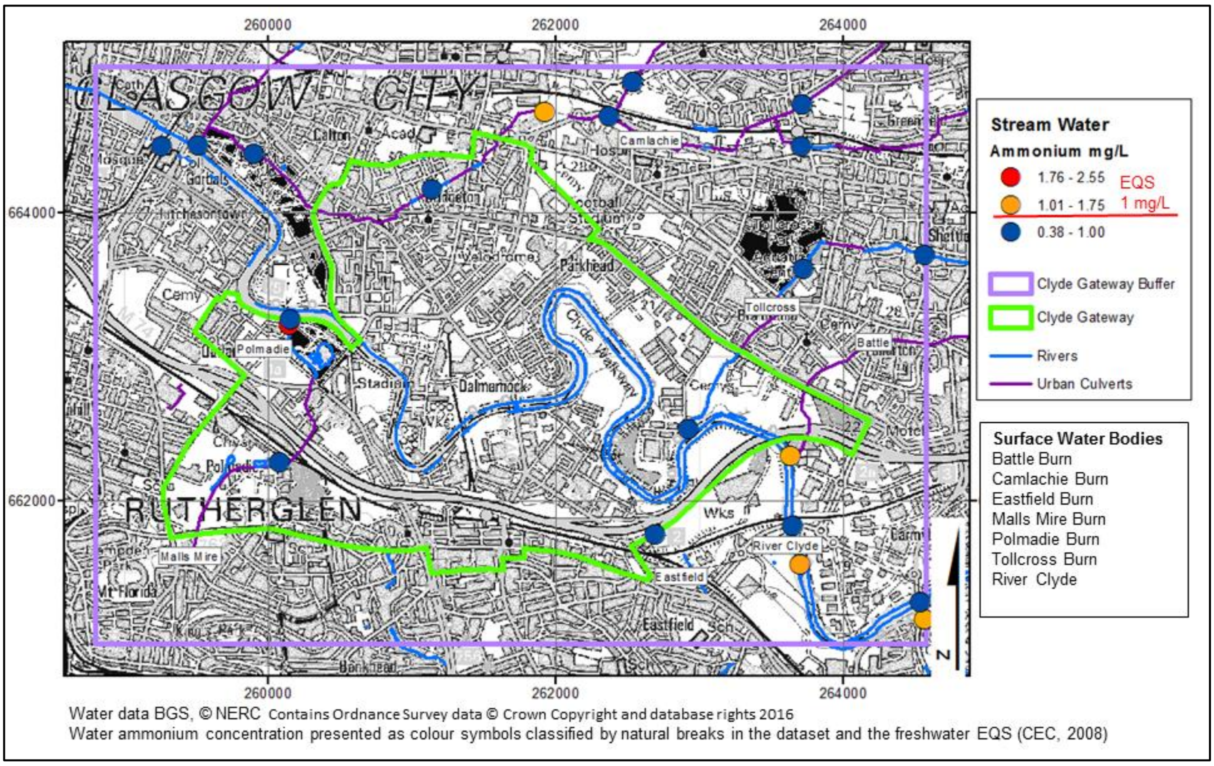


Figure 79 Ammonium concentration in stream water across the Clyde Gateway area collected in 2003. Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2017. Licence number 100021290 EUL

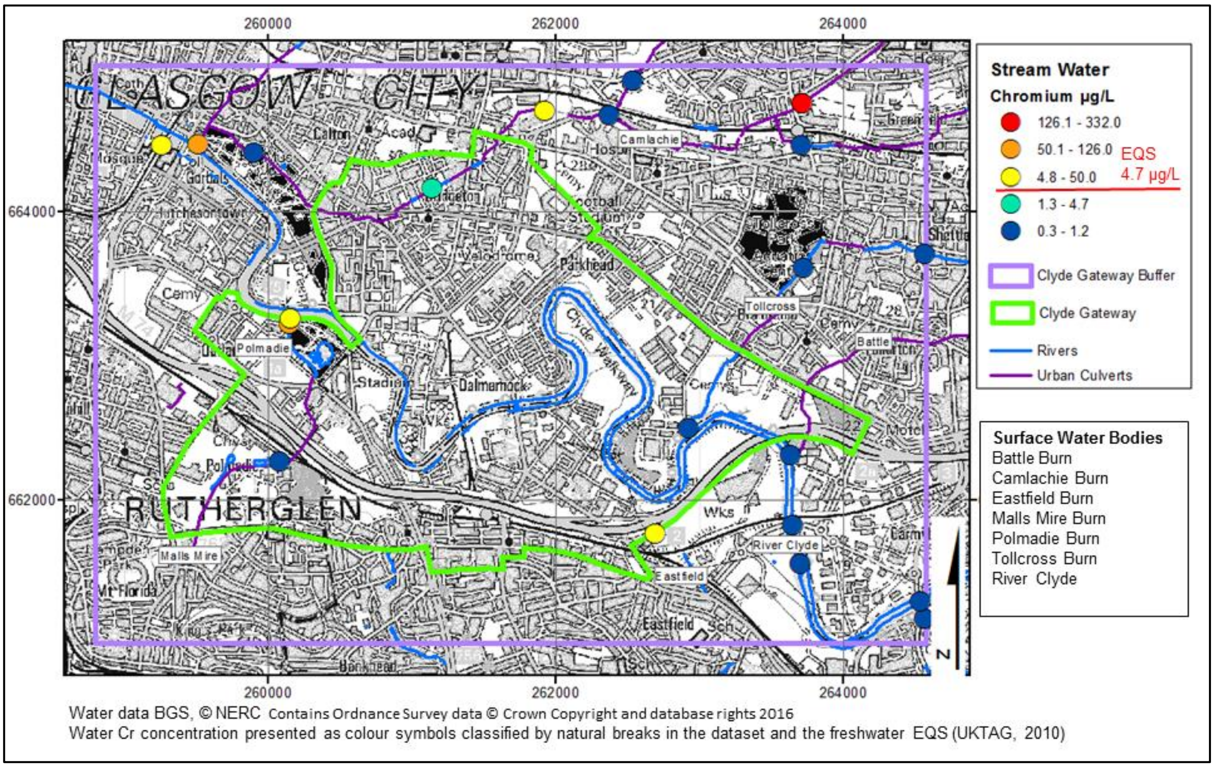


Figure 80 Chromium concentration in stream water across the Clyde Gateway area collected in 2003. Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2017. Licence number 100021290 EUL

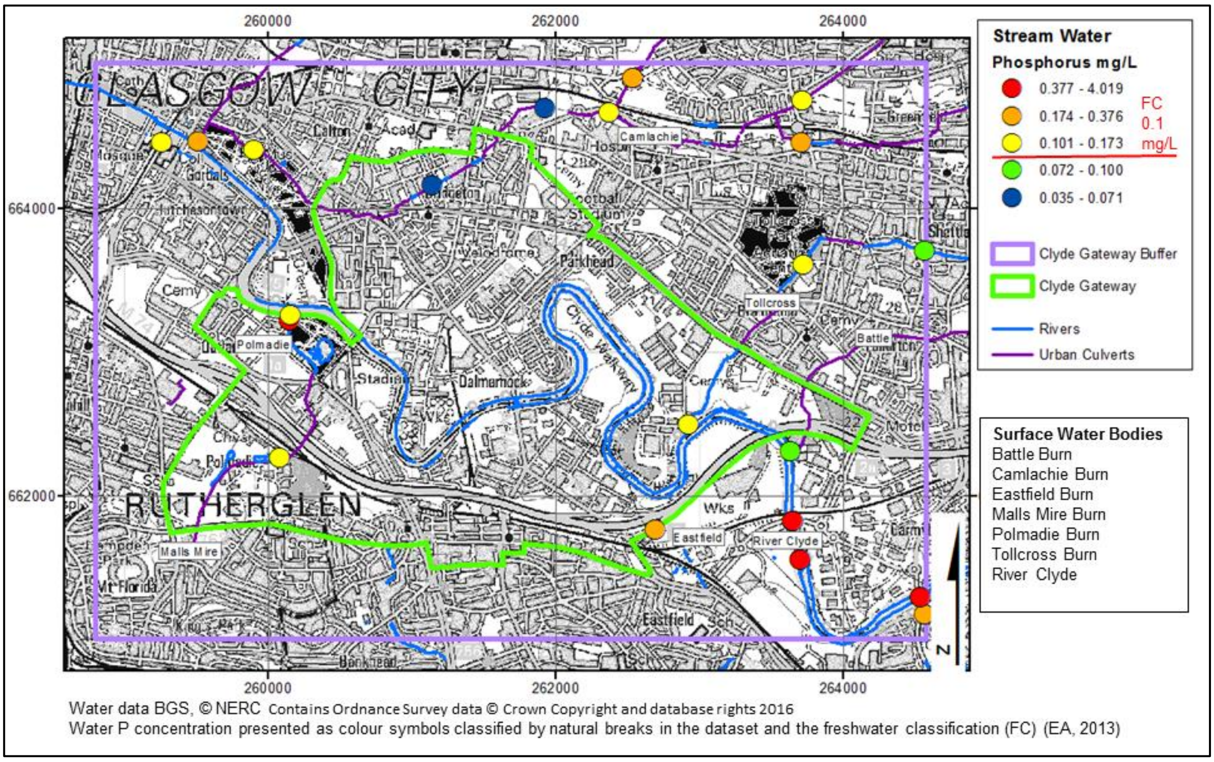


Figure 81 Phosphorus concentration in stream water across the Clyde Gateway area collected in 2003. Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2017. Licence number 100021290 EUL

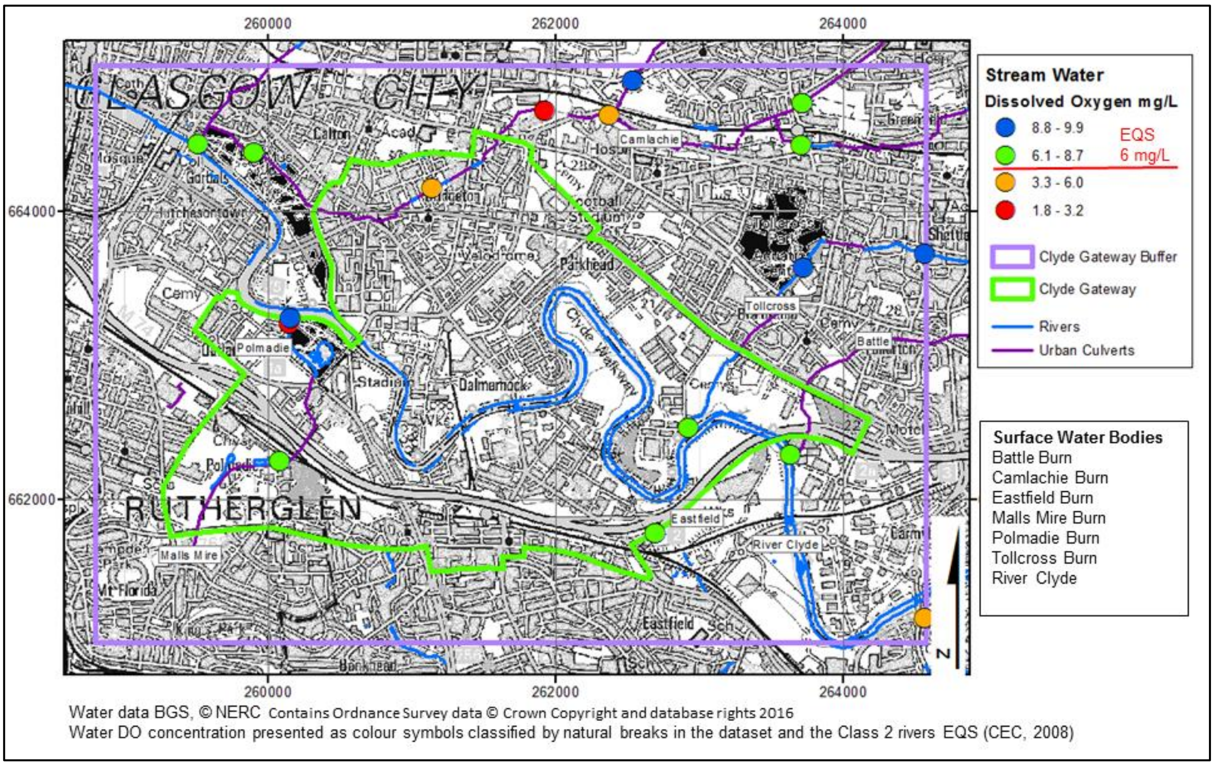


Figure 82 Dissolved oxygen (DO) concentration in stream water across the Clyde Gateway area collected in 2003. Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2017. Licence number 100021290 EUL

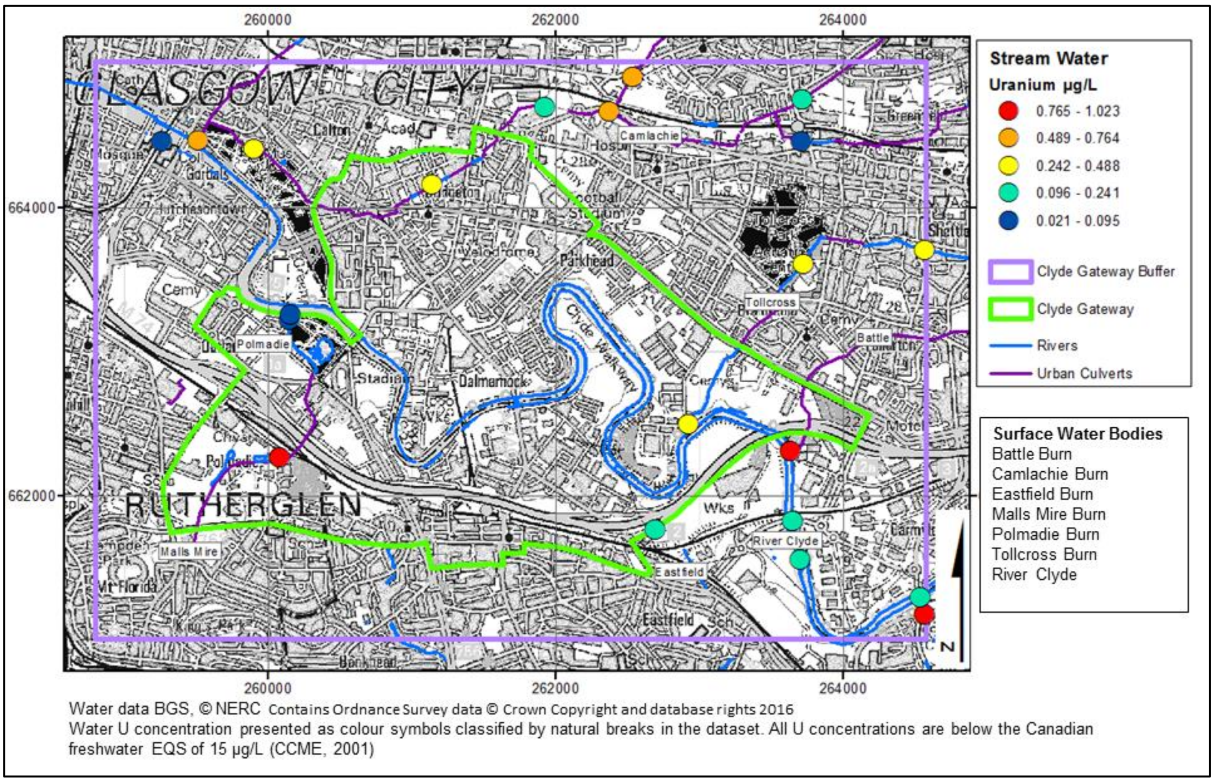


Figure 83 Uranium concentration in stream water across the Clyde Gateway area collected in 2003. Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2017. Licence number 100021290 EUL

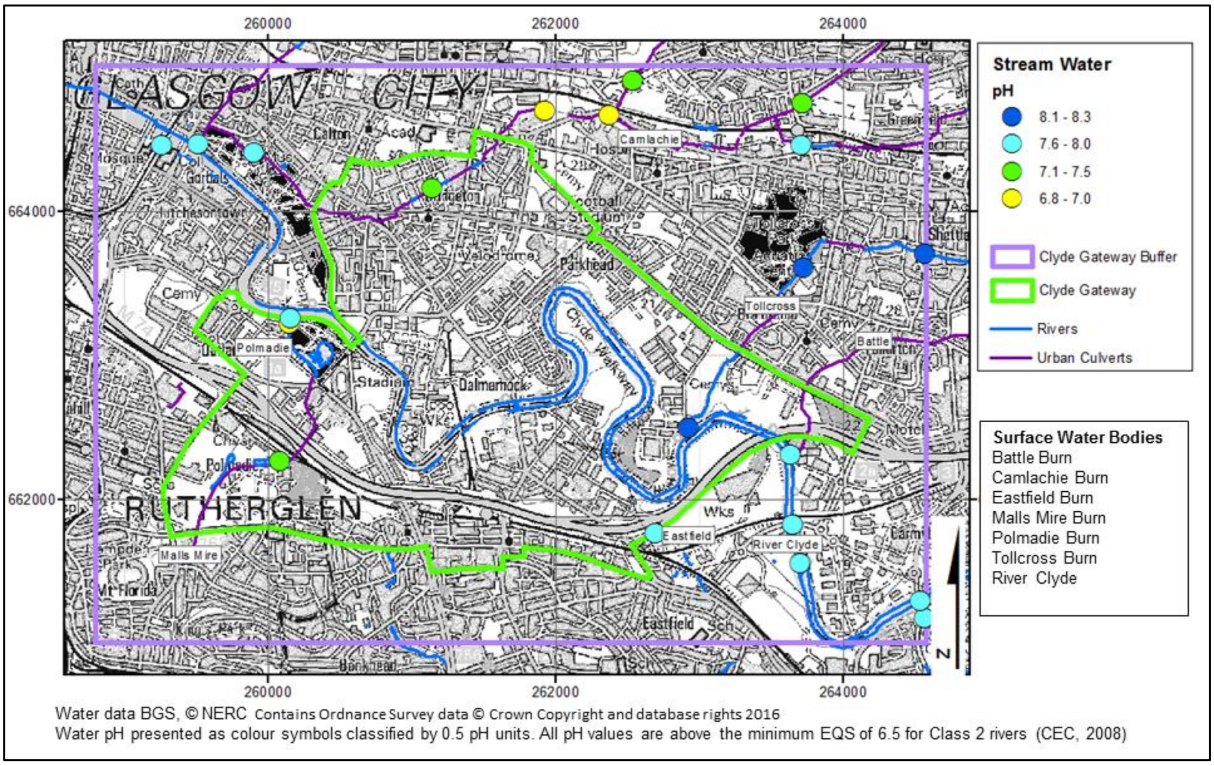


Figure 84 Stream water pH across the Clyde Gateway area collected in 2003. Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2017. Licence number 100021290 EUL

Appendix 2 Summary geotechnical data graphs

The summary graphs of geotechnical (engineering geology) data show different data and information that can be used to indicate the ground conditions for each of the superficial and bedrock units (see section 7 above). This includes the consistency for fine soils (very soft to very stiff), density for coarse soils (very loose to very dense) and strength (very weak to extremely strong). Other graphs show field or laboratory data.

Standard penetration test (SPT) N-values are used to indicate the relative density of coarse soils and strength of fine soils. There are various correlations that are used to estimate foundation in particular for piling.

Plasticity charts are used to classify fine soils as clays (above the A-line) and silt (below the A-line) and classification of the plasticity (low to extremely high), which can be used to indicate shrink swell characteristics and likely strength as water content changes, permeability and some shear strength parameters (angle of internal friction and residual strength).

Particle size distribution is used in engineering classification particularly for coarse soils but also for use in construction. The data presented here are where there are few data as individual samples, but for those units with many data they are summarised as percentiles, the number of percentiles shown depends on the number of samples. The particle size distribution shows how variable a unit is, for instance the Wilderness Till and the Gourock formations are much more variable than the Paisley and Ross members.

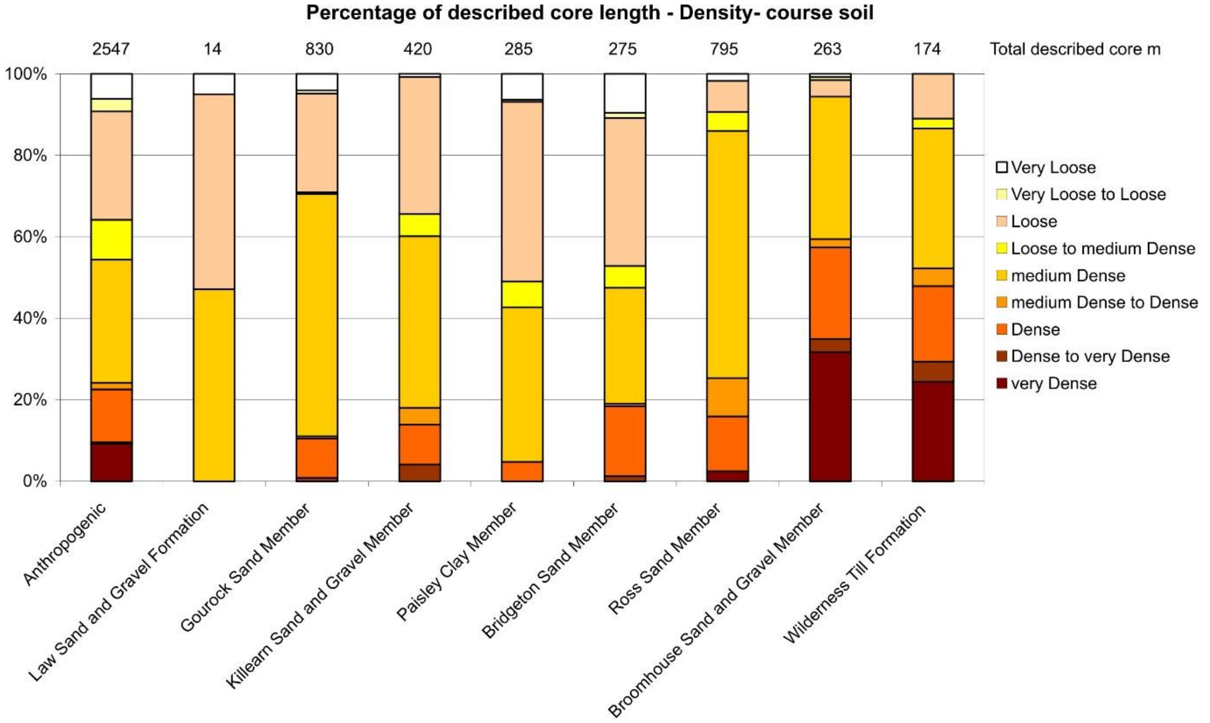
The use of undrained shear strength includes the calculation of the short term strength of fine soils for foundation bearing capacity and the stability of excavations. The consistency descriptions have been used in the past to indicate the undrained shear strength classes, but this is no longer the case, although they can be used to provide an idea of this strength.

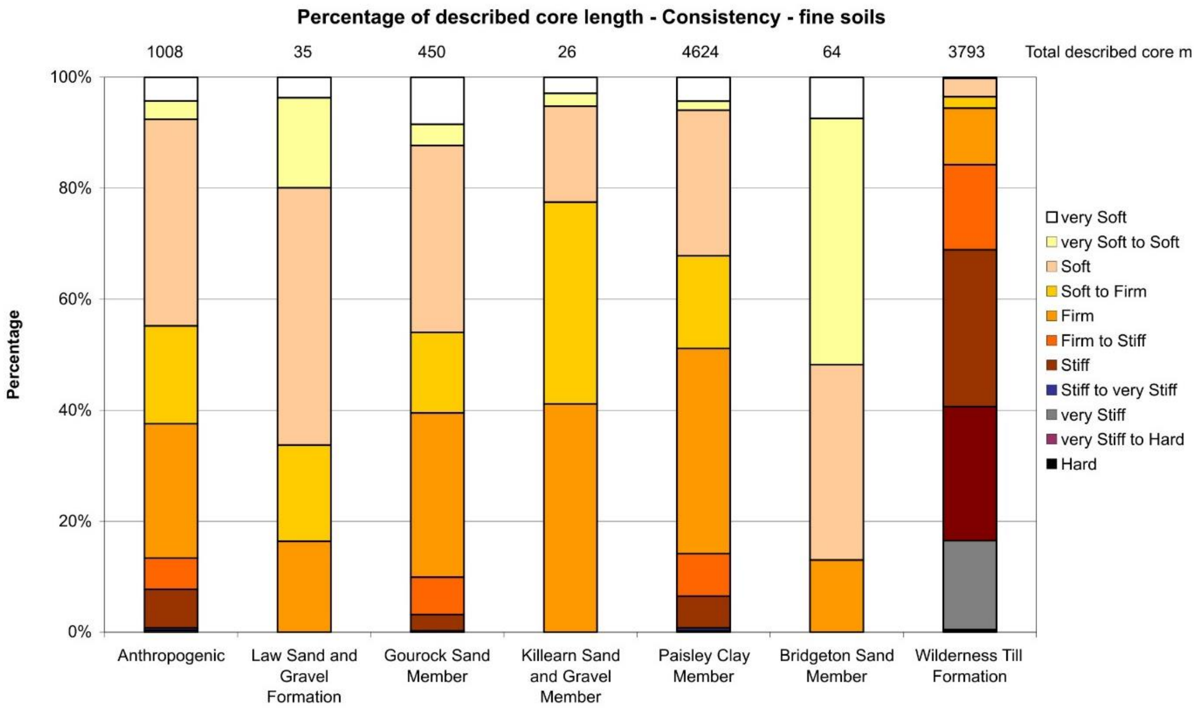
The uniaxial compressive strength of bedrock is a classification and characterisation test. It can be used to identify if certain types of drilling is suitable and, with discontinuity data, the stability of slopes, or excavations (at surface or beneath the ground) and excavatability.

Graphs

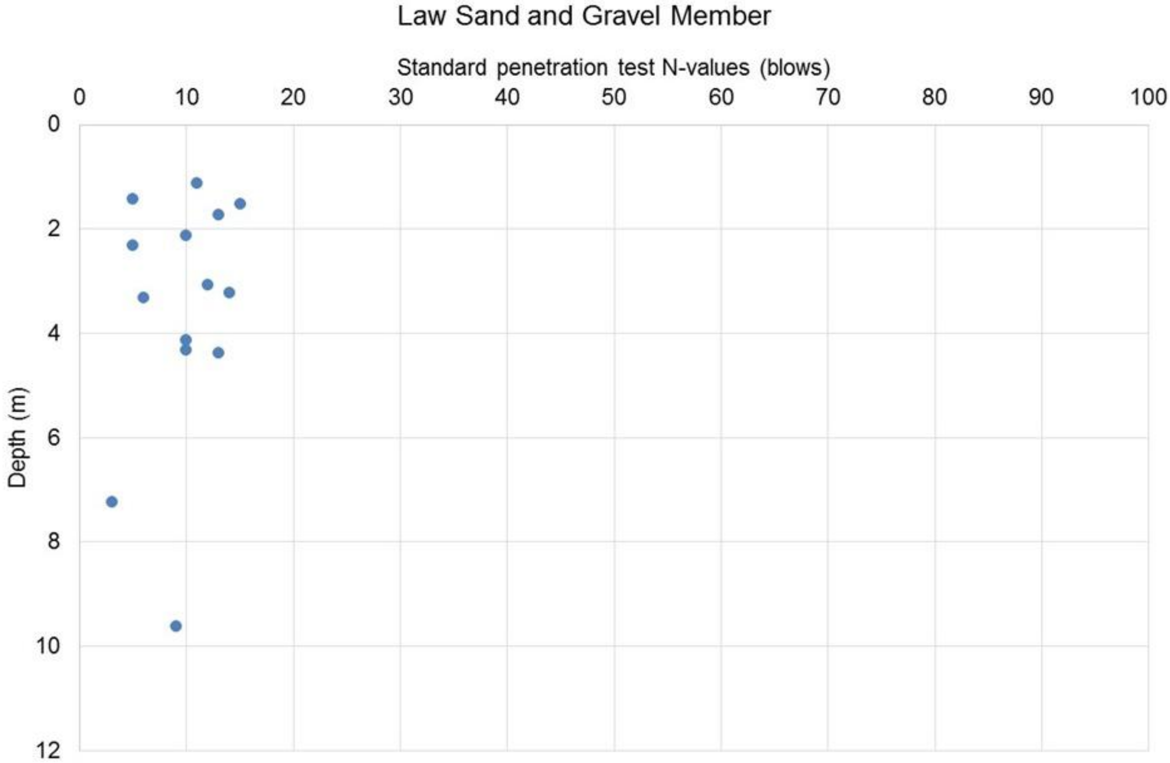
This section presents the data and information in a number of different ways: as summary bar graphs of superficial and bedrock units, consistency, density or strength descriptions at depth below surface, or below the top of the unit, and field and laboratory parameters, some plotted against depth below ground level. The extended box and whisker plots present various percentiles depending on the number of values and provide a rapid assessment of the data range and allow for easy comparison between different characteristics such as lithology.

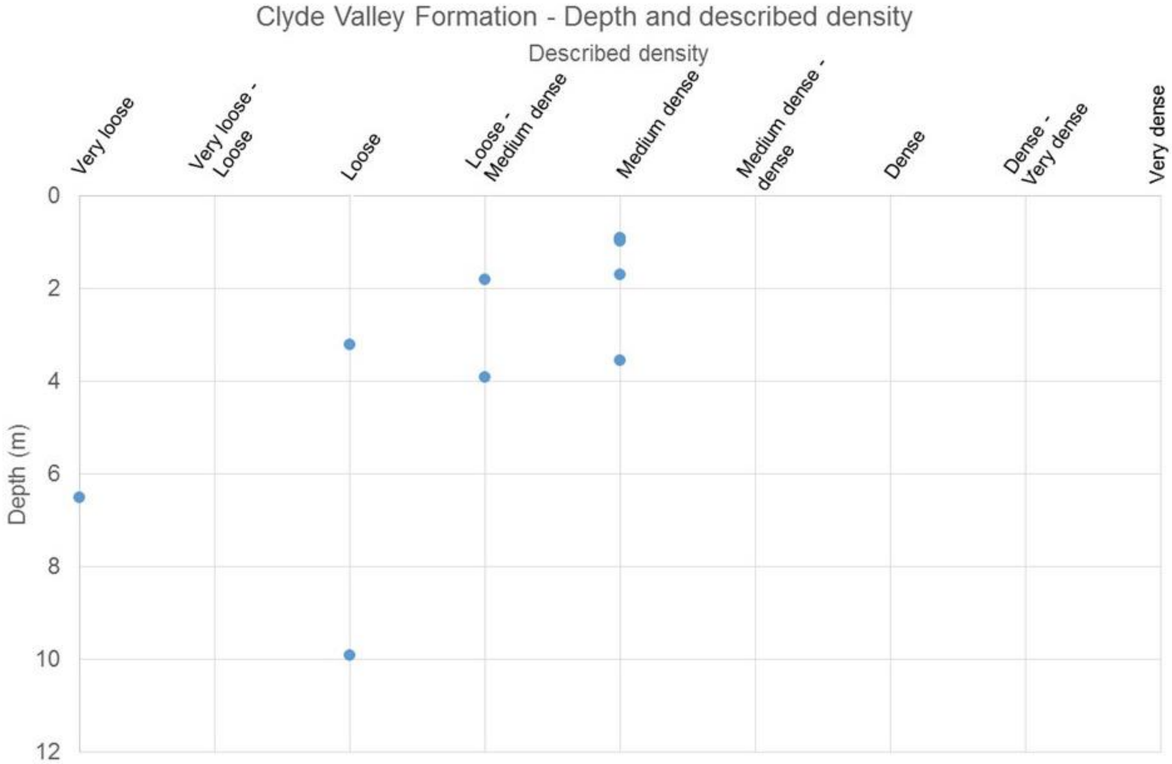
SUPERFICIAL UNITS

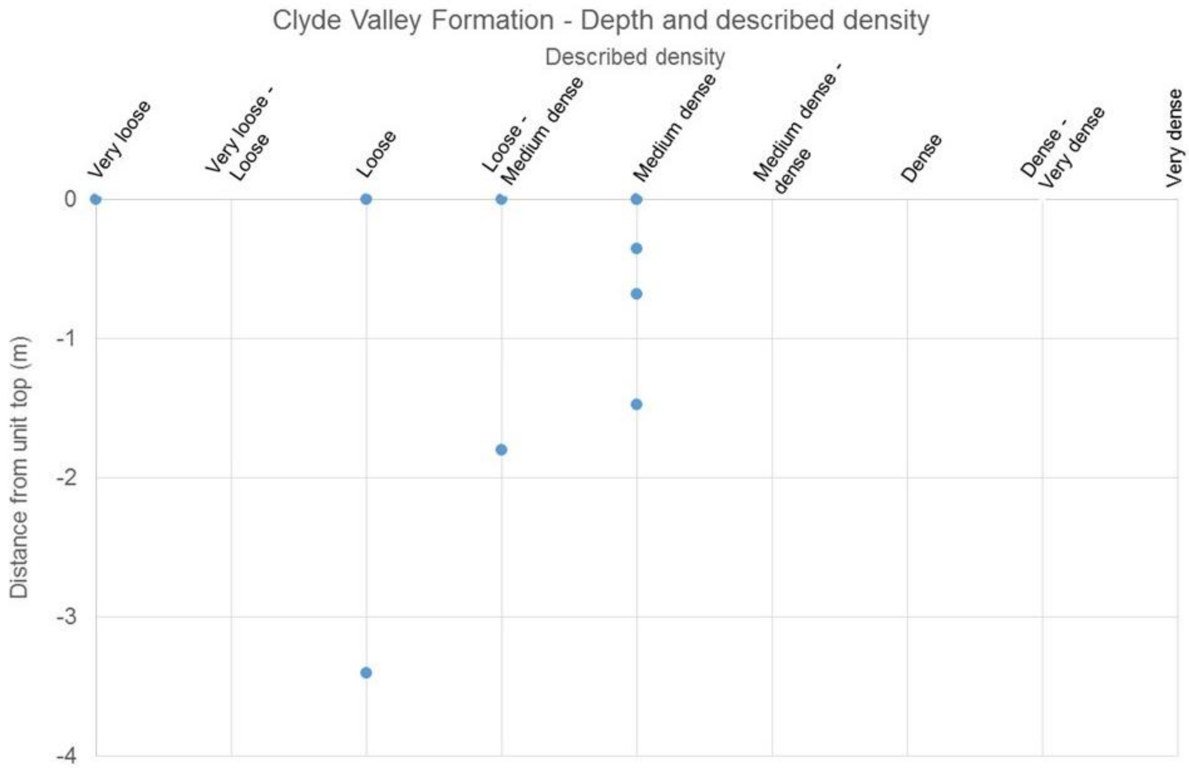




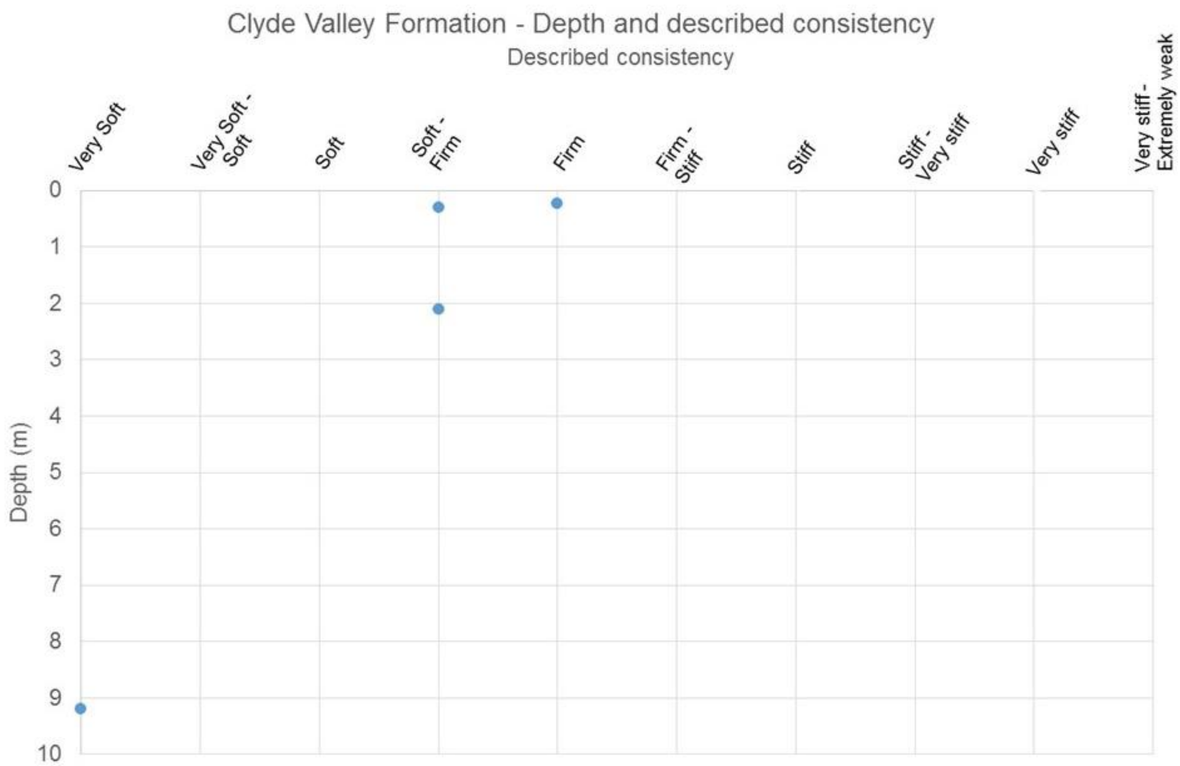
Clyde Valley Formation – Law Sand and Gravel Member



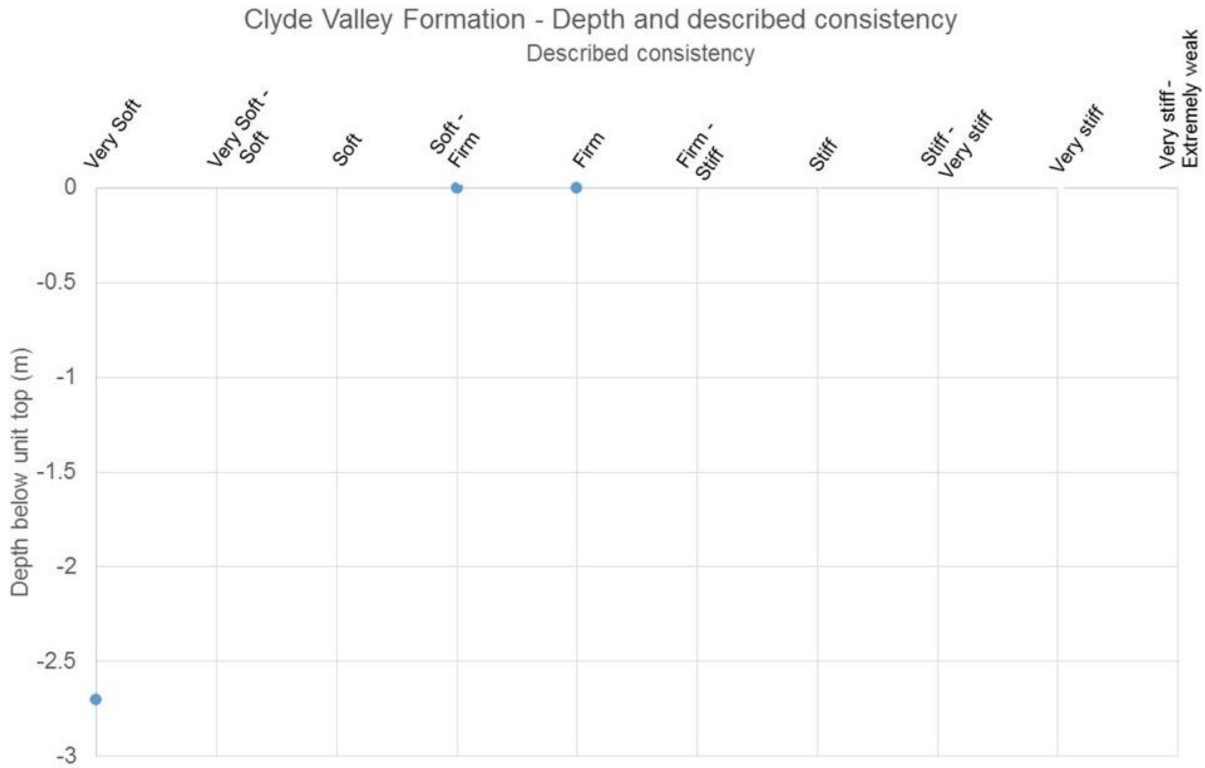




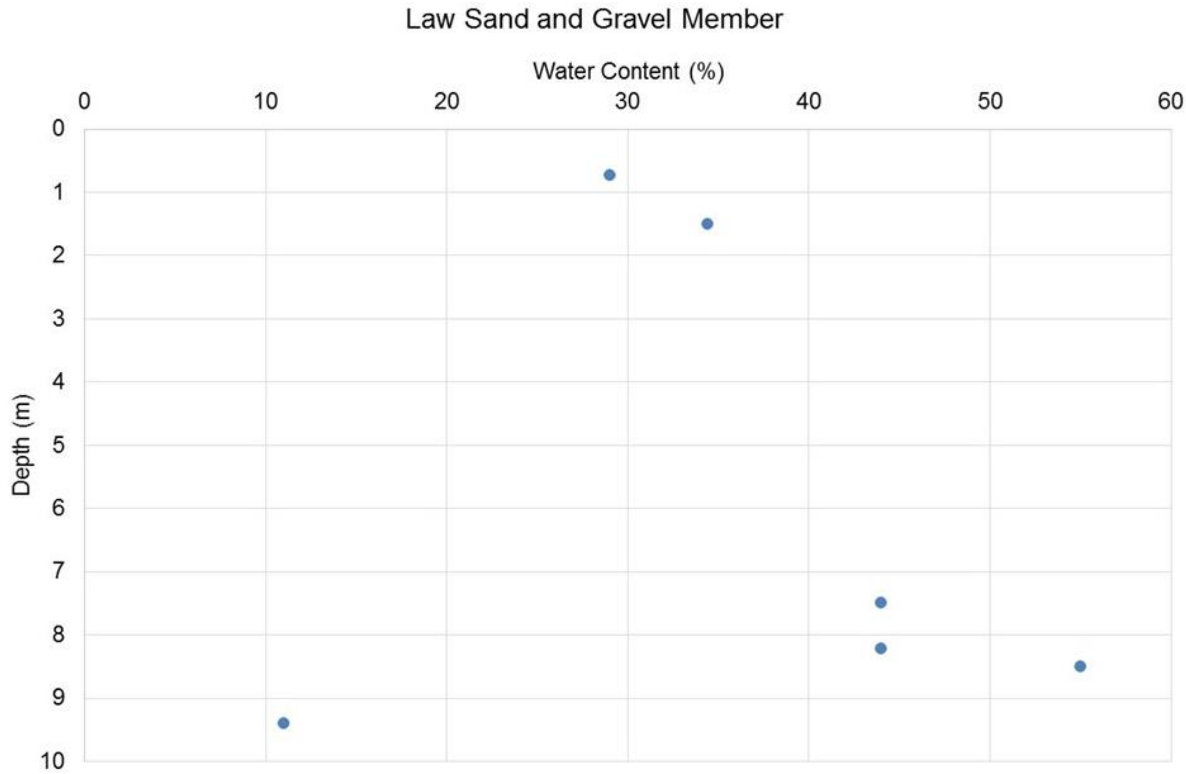
Clyde Valley Formation - Depth and described density
Described density
Very loose
Very loose - Loose
Loose
Loose - Medium dense
Medium dense
Medium dense - dense
Dense
Dense - Very dense
Very dense
Distance from unit top (m)
0
-1
-2
-3
-4



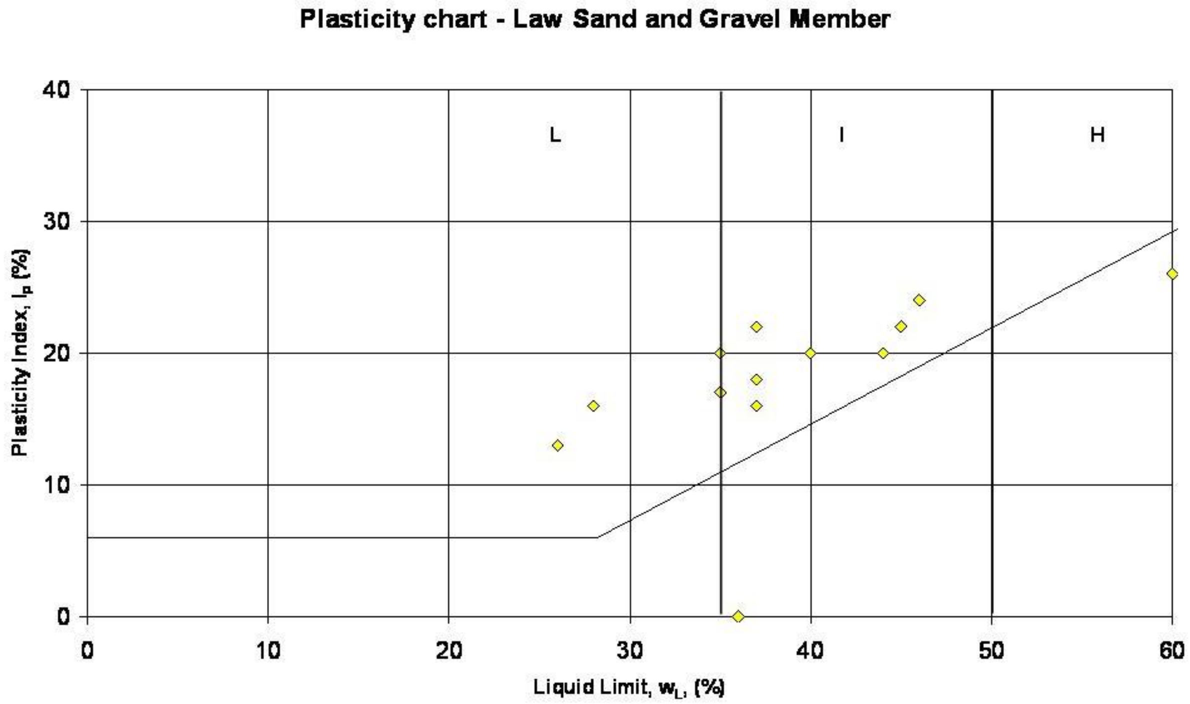
Clyde Valley Formation - Depth and described consistency
Described consistency
Very Soft
Very Soft - Soft
Soft
Soft - Firm
Firm
Firm - Stiff
Stiff
Stiff - Very stiff
Very stiff
Very stiff - Extremely weak
Depth (m)
0
1
2
3
4
5
6
7
8
9
10

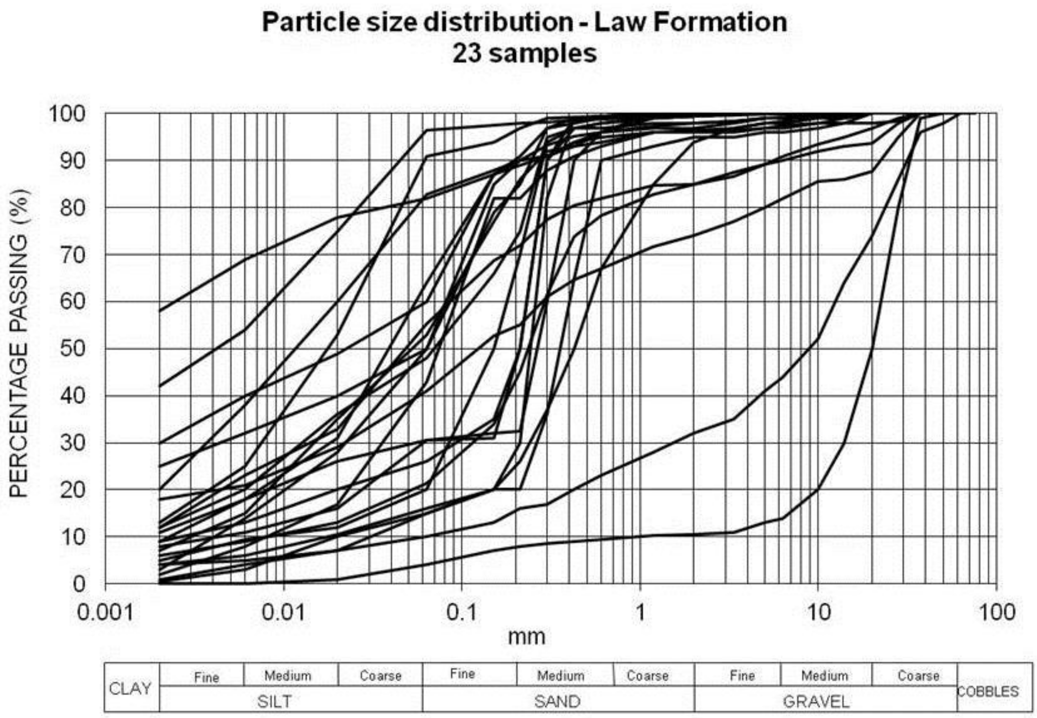


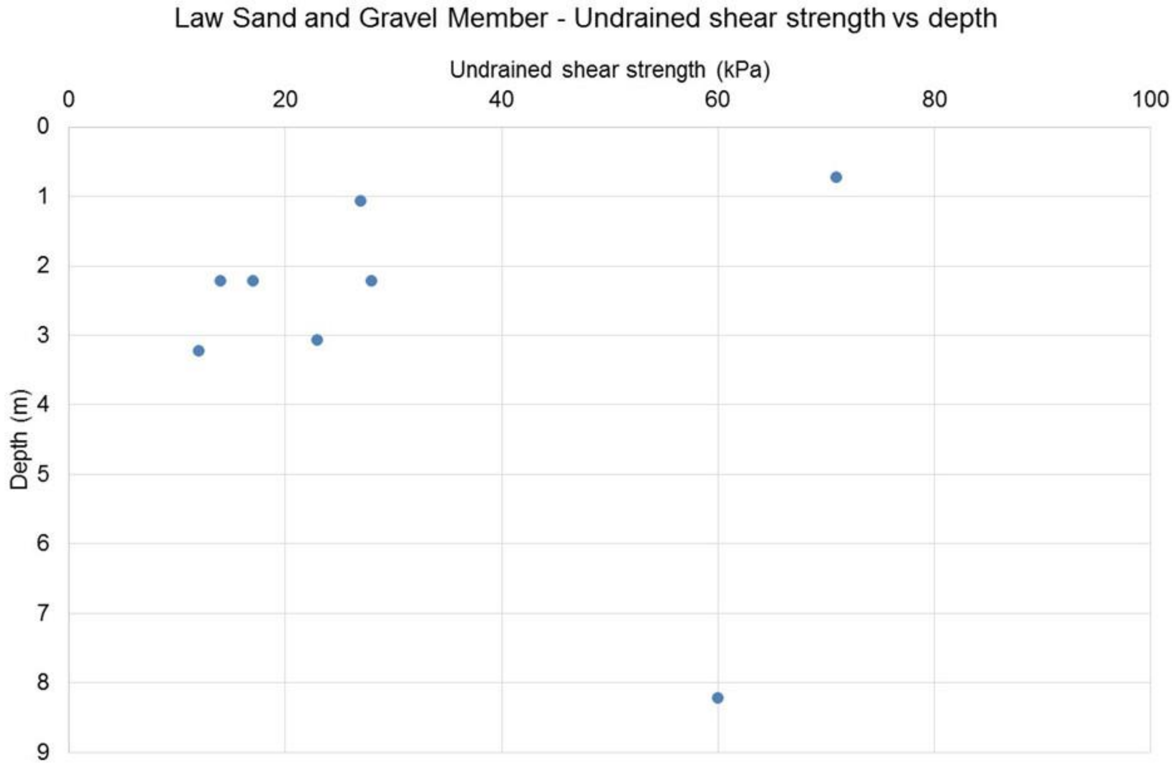
Clyde Valley Formation - Depth and described consistency
Described consistency
Very Soft
Very Soft - Soft
Soft
Soft - Firm
Firm
Firm - Stiff
Stiff
Stiff - Very stiff
Very stiff
Very stiff - Extremely weak
Depth below unit top (m)
0
-0.5
-1
-1.5
-2
-2.5
-3

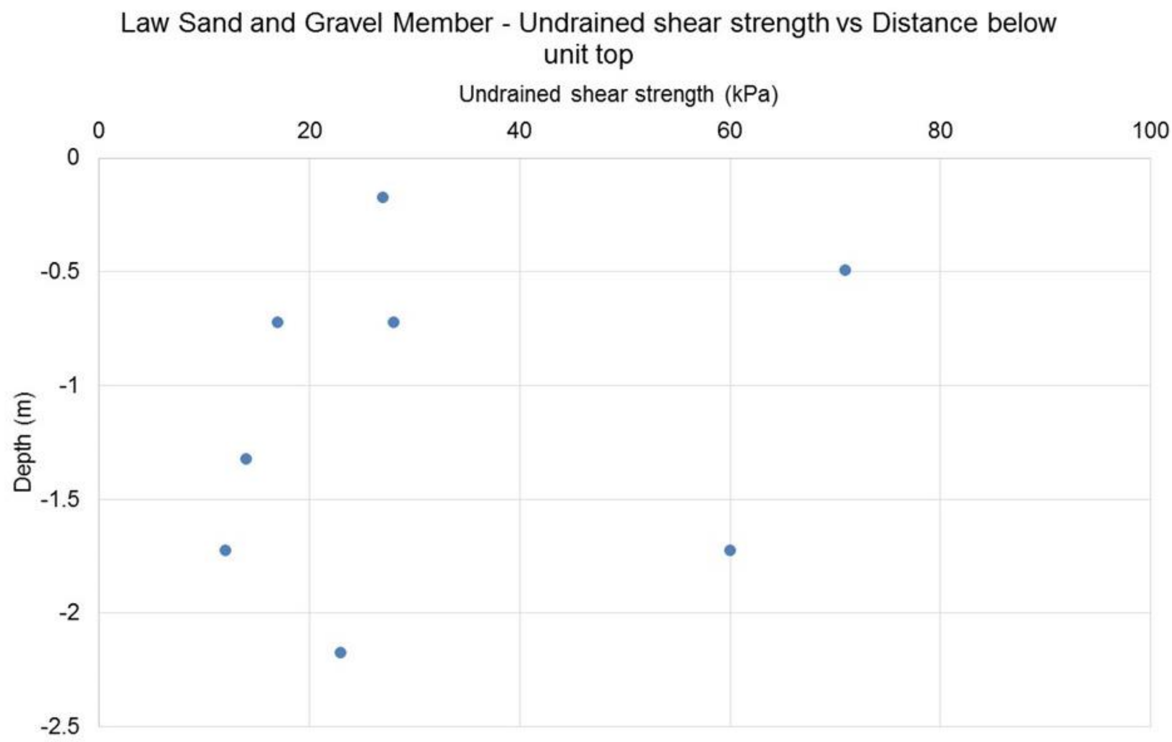


Law Sand and Gravel Member
Water Content (%)
0
10
20
30
40
50
60
Depth (m)
0
1
2
3
4
5
6
7
8
9
10

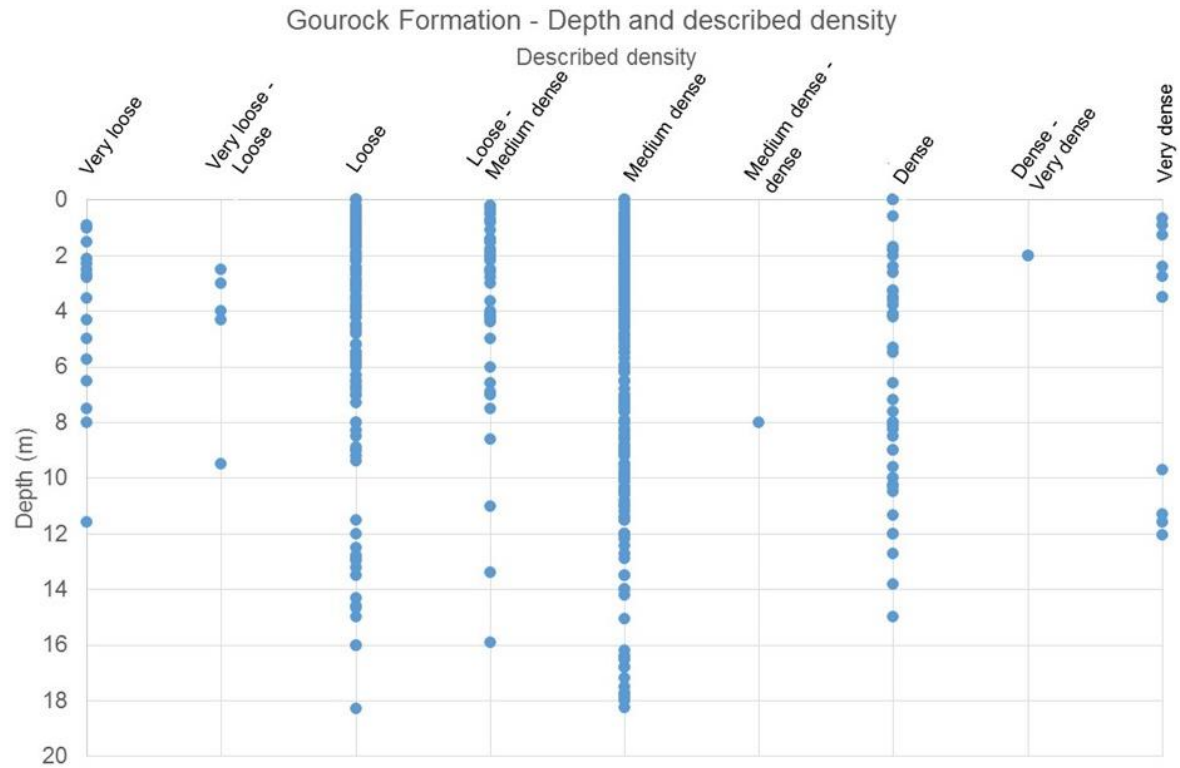

Plasticity chart - Law Sand and Gravel Member
L
I
H
Plasticity Index, I_p (%)
Liquid Limit, w_L, (%)
0
10
20
30
40
50
60

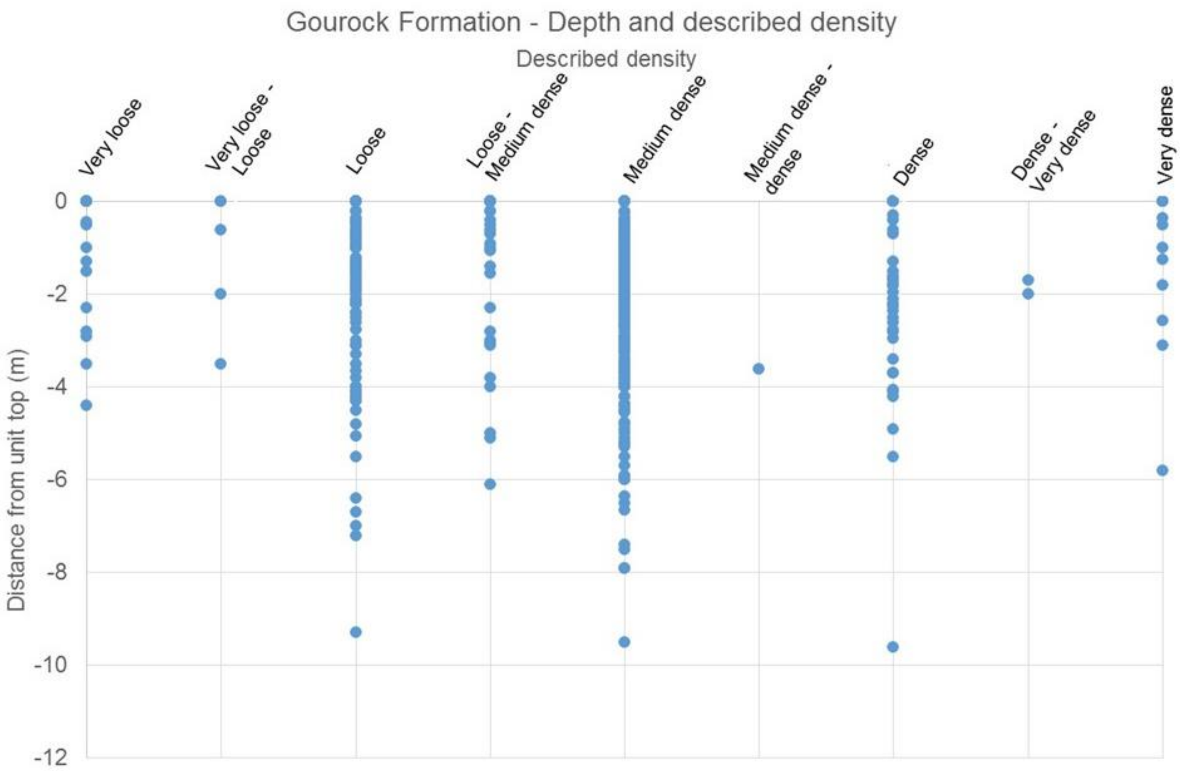

Particle size distribution - Law Formation
23 samples
PERCENTAGE PASSING (%)
mm
0.001
0.01
0.1
1
10
100
CLAY
Fine
Medium
Coarse
SILT
SAND
GRAVEL
COBBLES

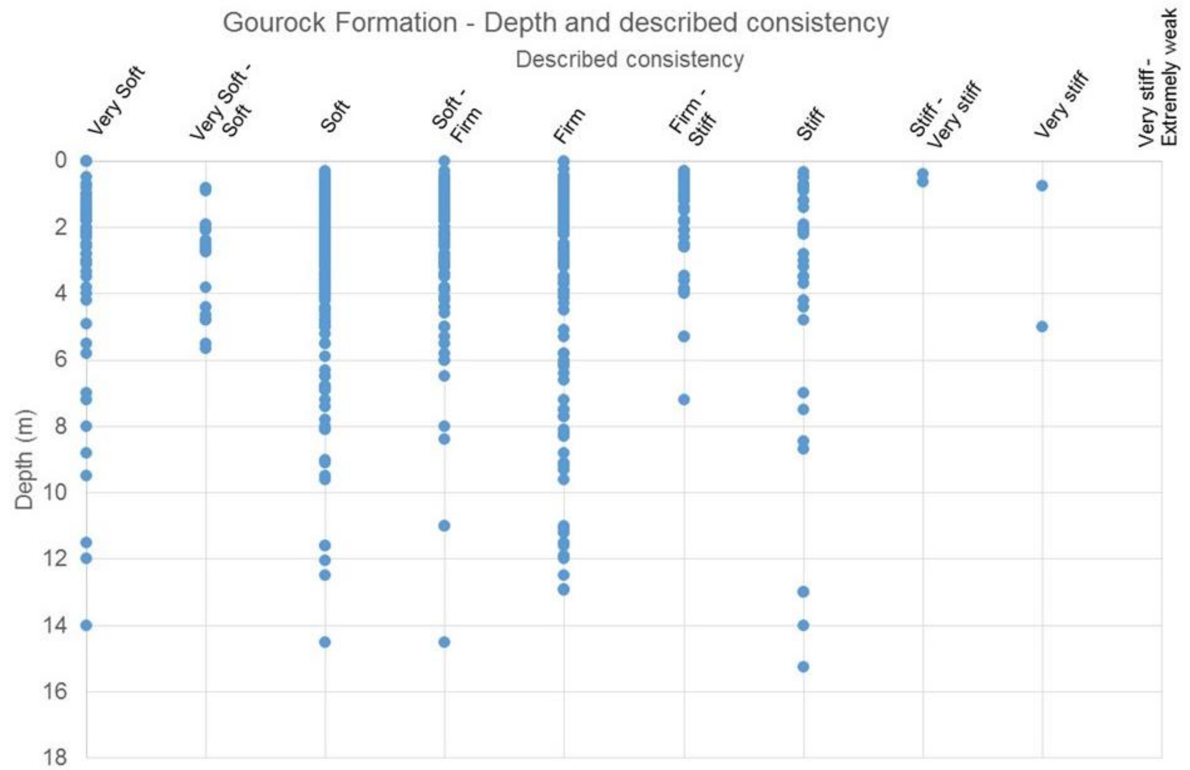

Law Sand and Gravel Member - Undrained shear strength vs depth
Undrained shear strength (kPa)
0
20
40
60
80
100
Depth (m)
0
1
2
3
4
5
6
7
8
9

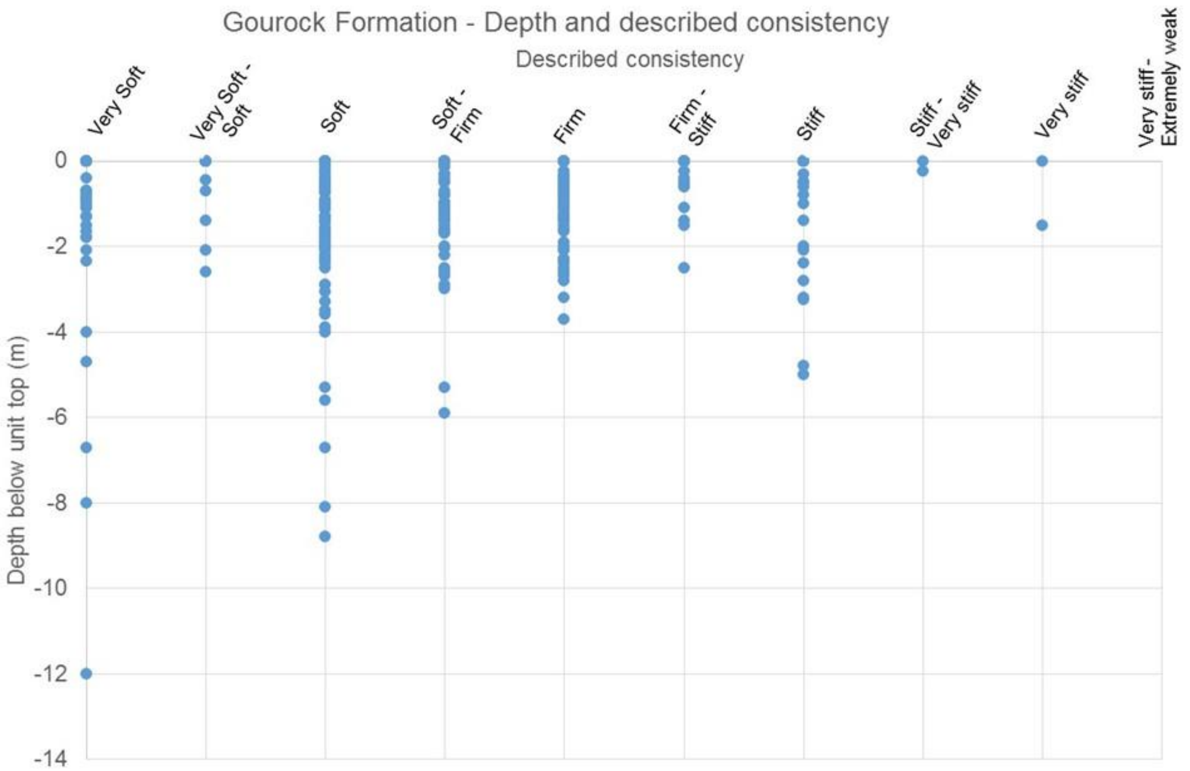

Law Sand and Gravel Member - Undrained shear strength vs Distance below unit top
Undrained shear strength (kPa)
0
20
40
60
80
100
Depth (m)
0
-0.5
-1
-1.5
-2
-2.5

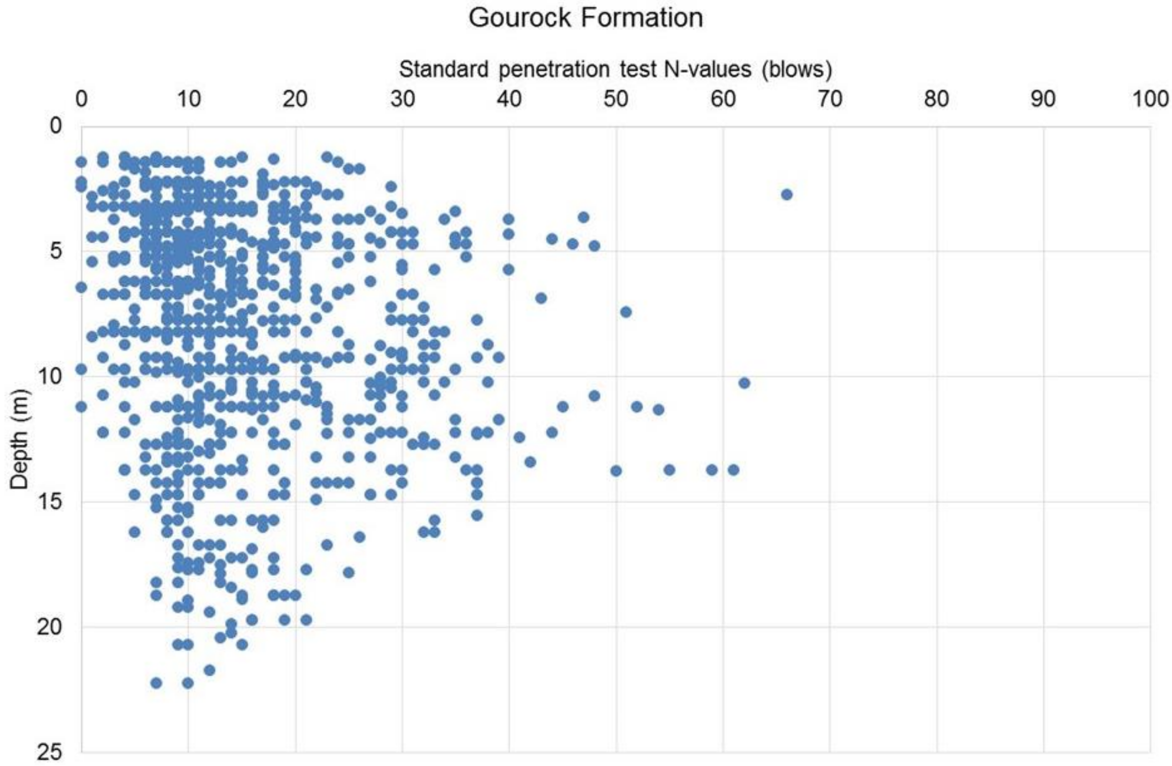
Gourock Formation

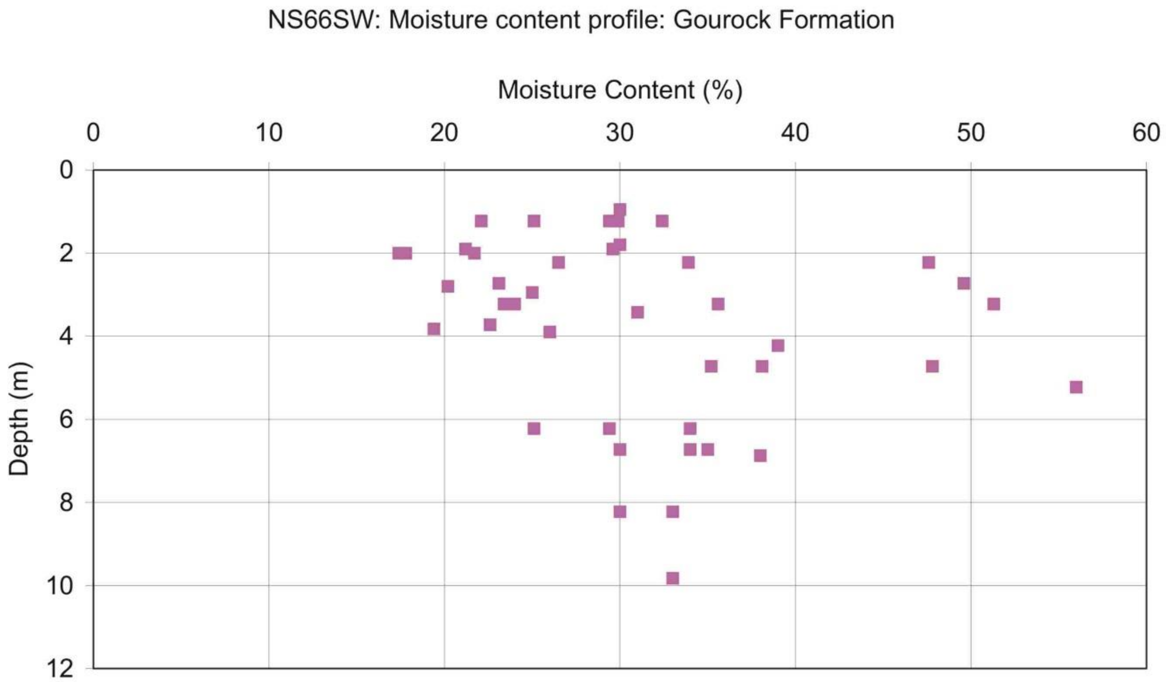


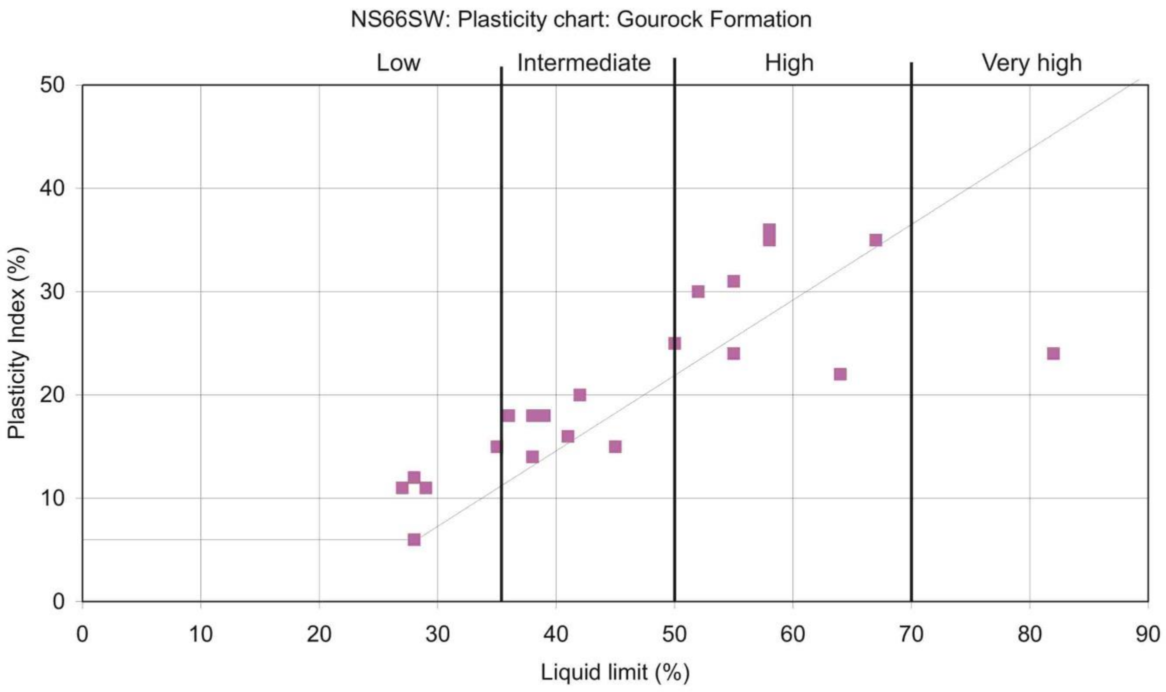


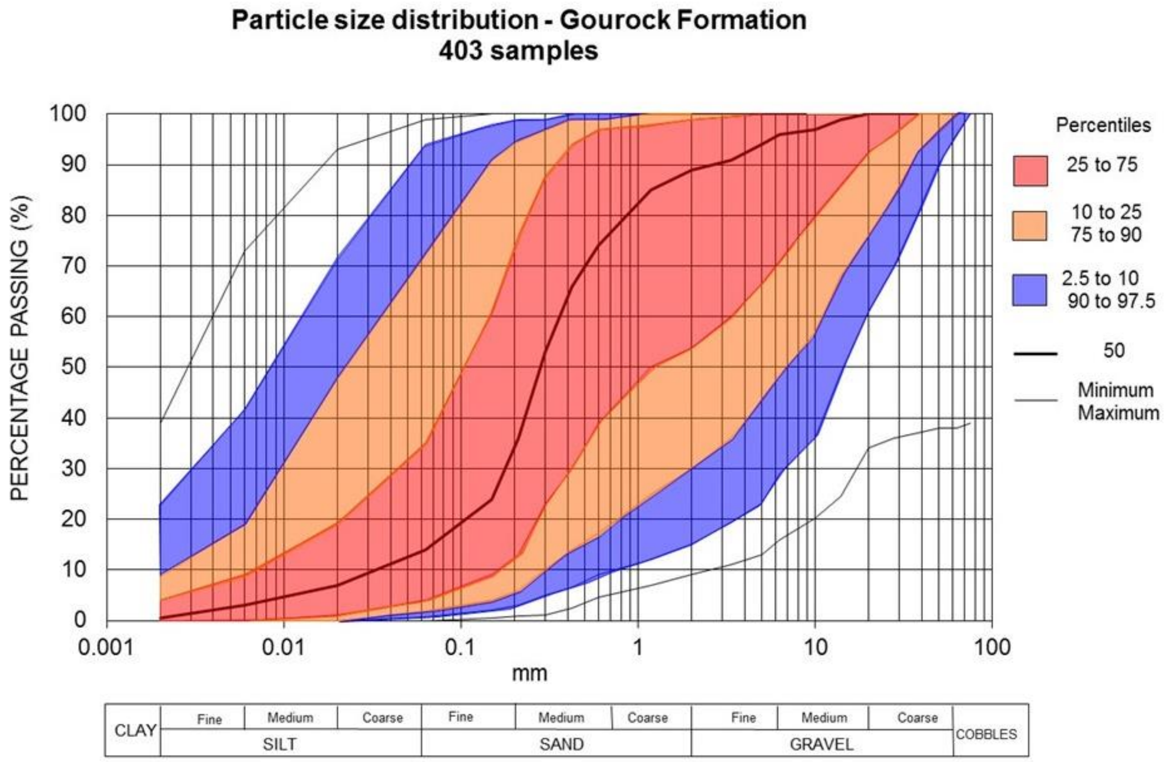

Gourock Formation - Depth and described consistency
Described consistency
Very Soft
Very Soft - Soft
Soft
Soft - Firm
Firm
Firm - Stiff
Stiff
Stiff - Very stiff
Very stiff
Very stiff - Extremely weak
Depth (m)
0
2
4
6
8
10
12
14
16
18

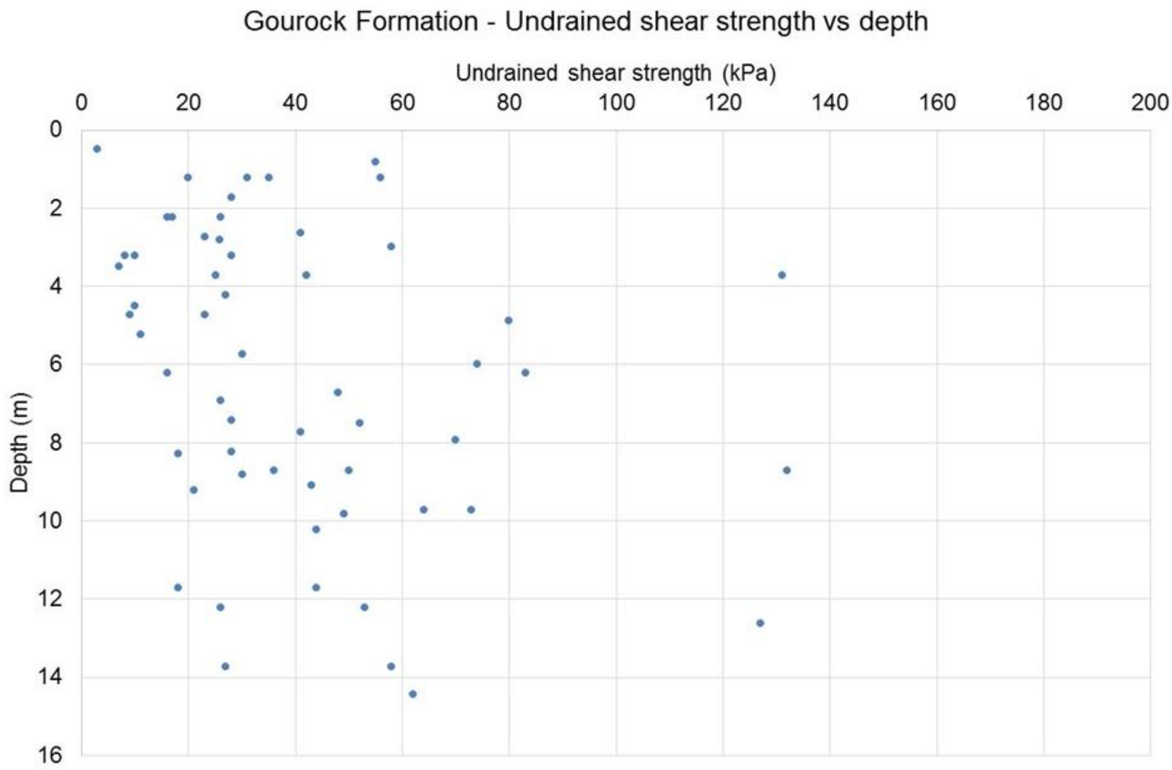

Gourock Formation - Depth and described consistency
Described consistency
Very Soft
Very Soft - Soft
Soft
Soft - Firm
Firm
Firm - Stiff
Stiff
Stiff - Very stiff
Very stiff
Very stiff - Extremely weak
Depth below unit top (m)
0
-2
-4
-6
-8
-10
-12
-14

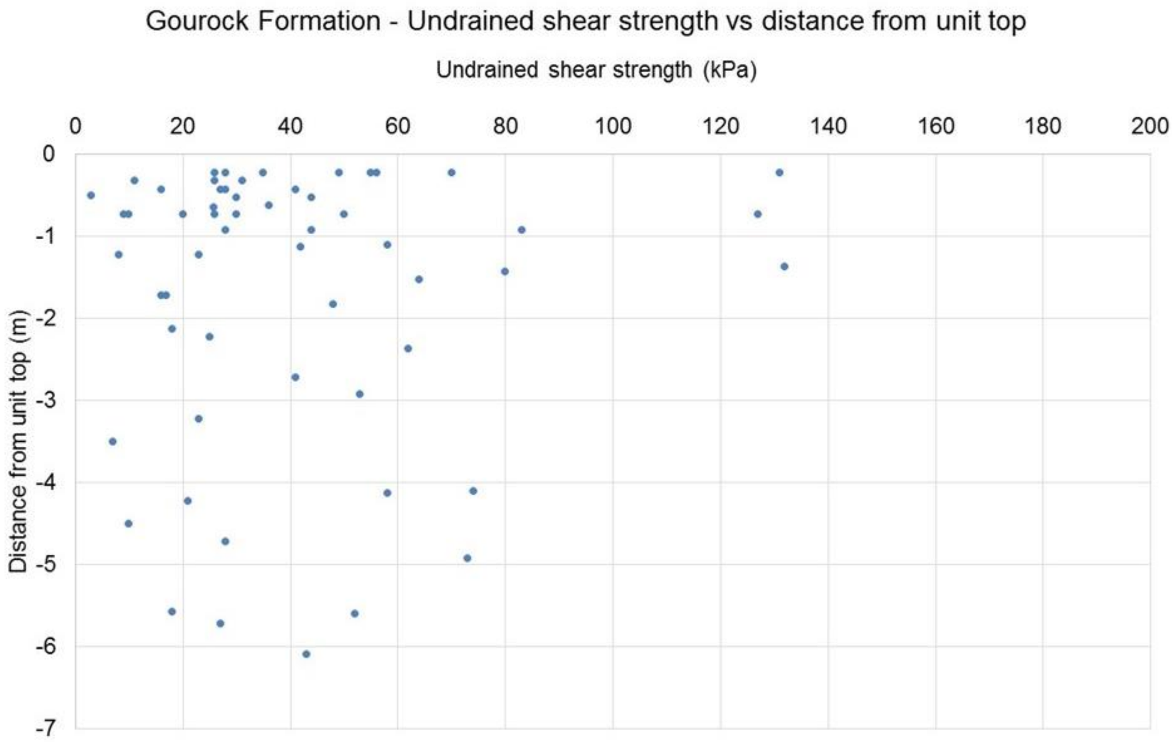

Gourock Formation
Standard penetration test N-values (blows)
0 10 20 30 40 50 60 70 80 90 100
Depth (m)
0 5 10 15 20 25

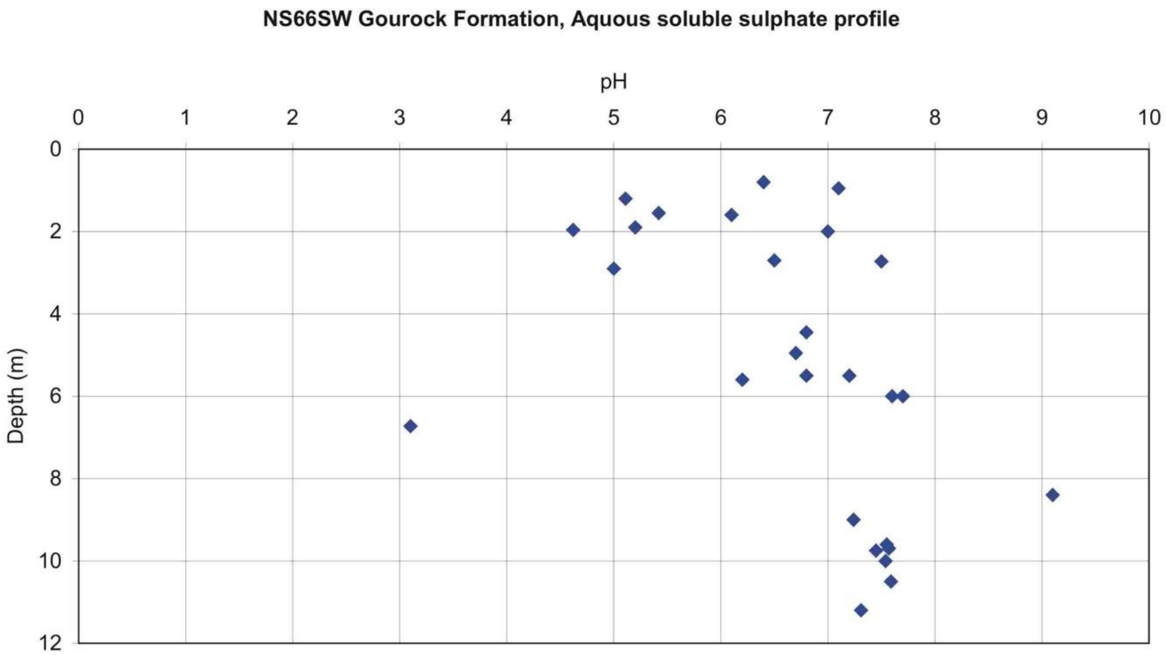

NS66SW: Moisture content profile: Gourock Formation
Moisture Content (%)
0 10 20 30 40 50 60
Depth (m)
0 2 4 6 8 10 12


NS66SW: Plasticity chart: Gourock Formation
Low
Intermediate
High
Very high
Plasticity Index (%)
Liquid limit (%)

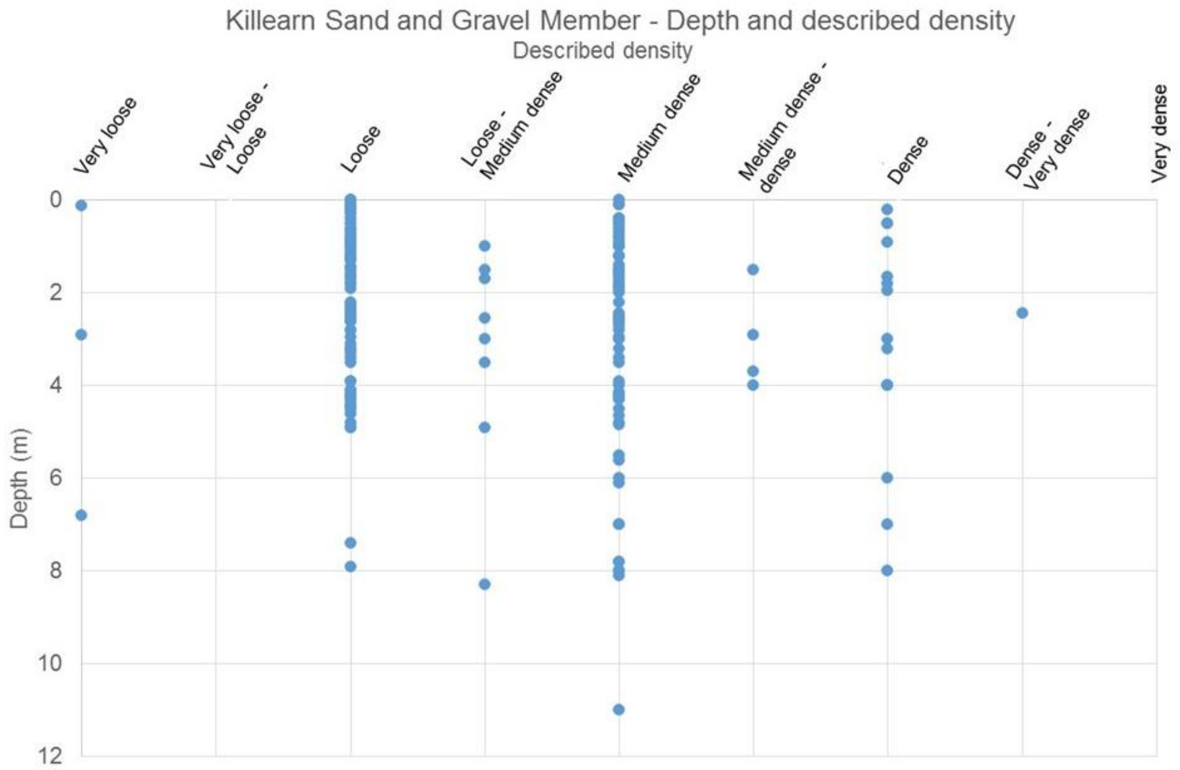

Particle size distribution - Gourock Formation
403 samples
PERCENTAGE PASSING (%)
mm
Percentiles
25 to 75
10 to 25
75 to 90
2.5 to 10
90 to 97.5
50
Minimum
Maximum
CLAY
Fine
Medium
Coarse
SILT
SAND
GRAVEL
COBBLES

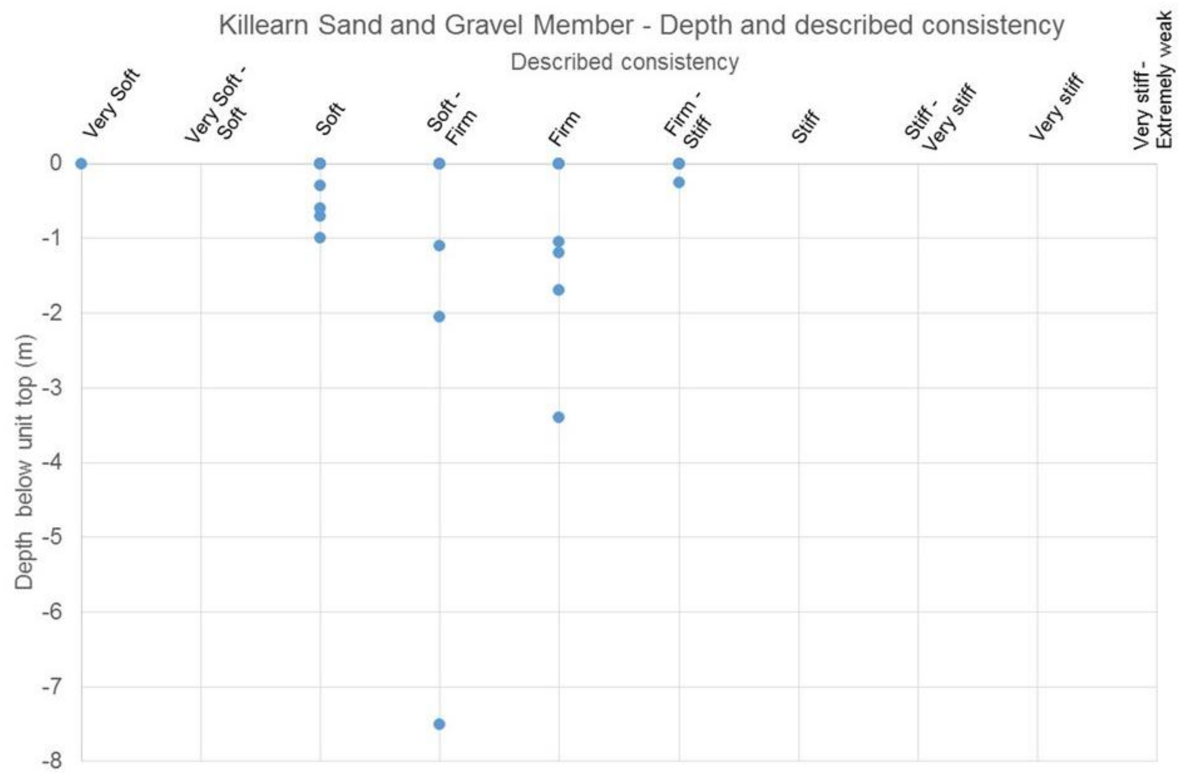

Gourock Formation - Undrained shear strength vs depth
Undrained shear strength (kPa)
0
20
40
60
80
100
120
140
160
180
200
Depth (m)
0
2
4
6
8
10
12
14
16

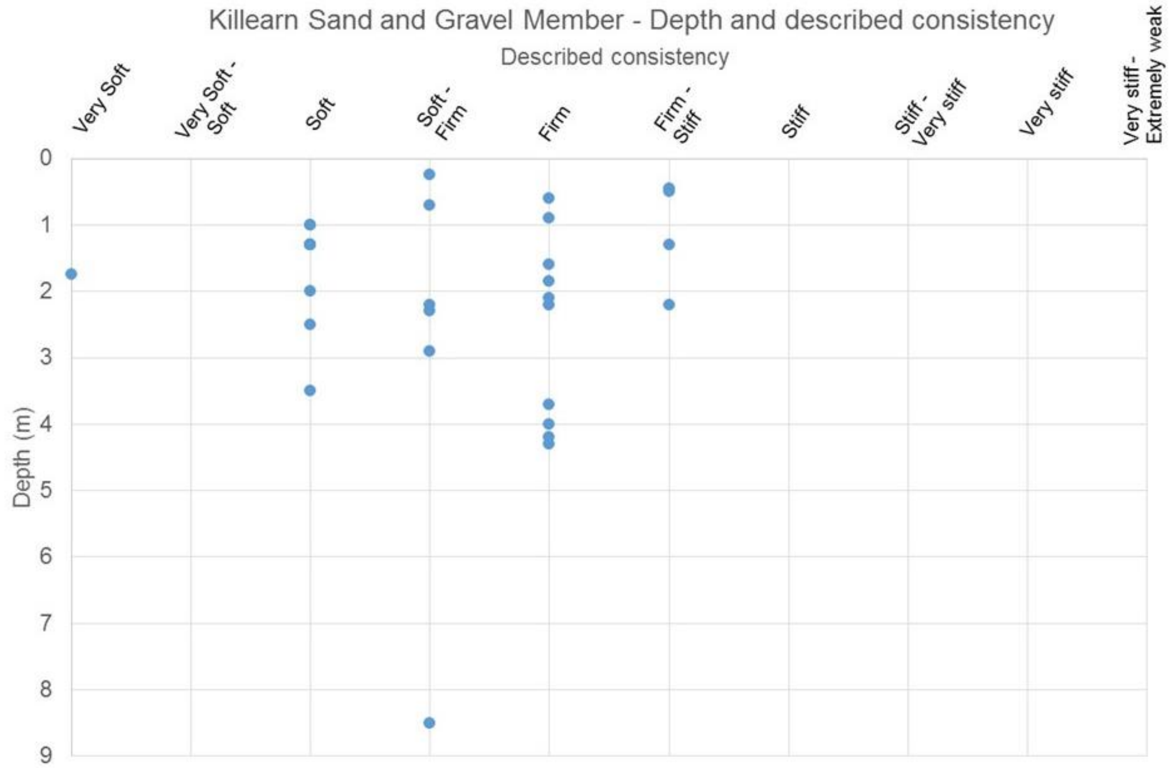

Gourock Formation - Undrained shear strength vs distance from unit top
Undrained shear strength (kPa)
0
20
40
60
80
100
120
140
160
180
200
Distance from unit top (m)
0
-1
-2
-3
-4
-5
-6
-7

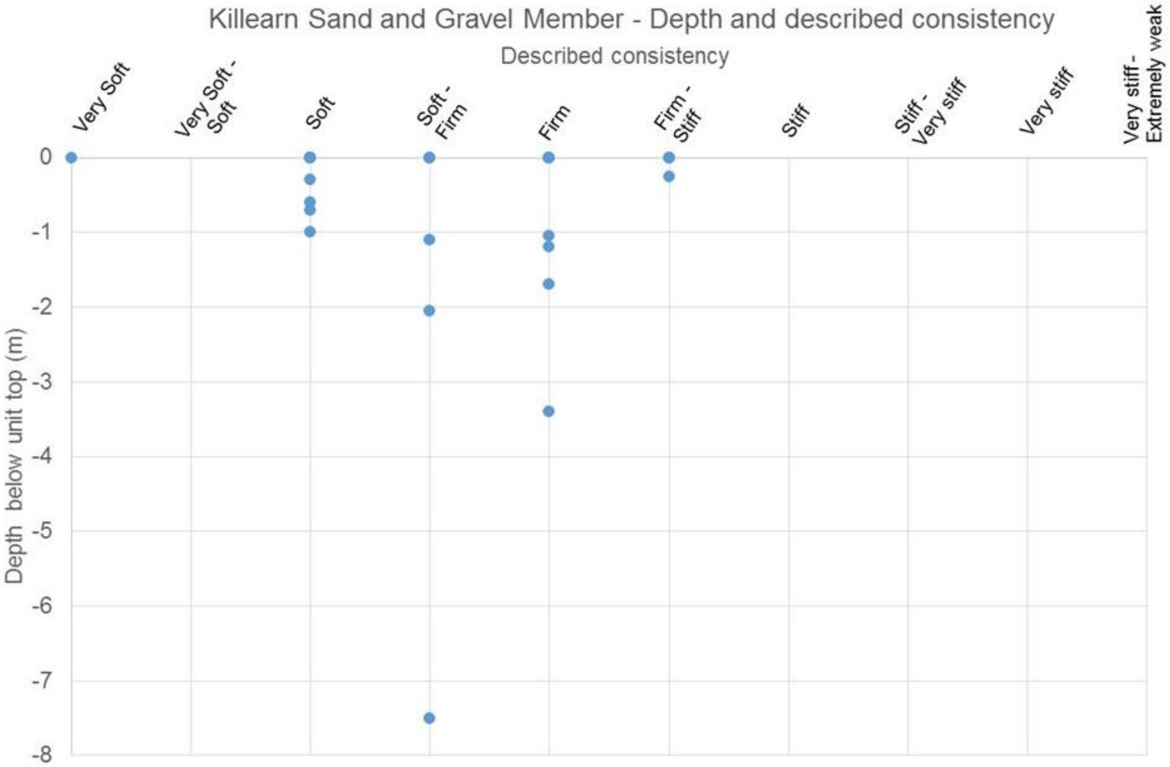

NS66SW Gourock Formation, Aquous soluble sulphate profile
pH
0
1
2
3
4
5
6
7
8
9
10
Depth (m)
0
2
4
6
8
10
12

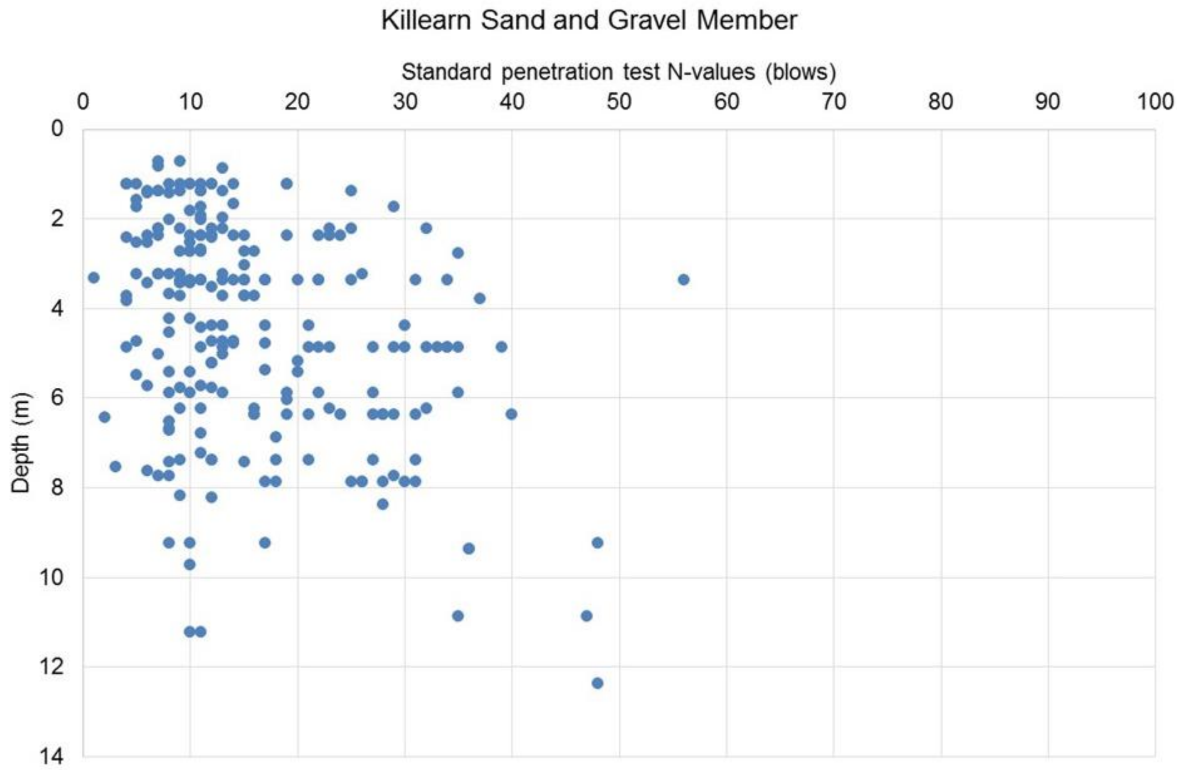
Killearn Sand and Gravel Member





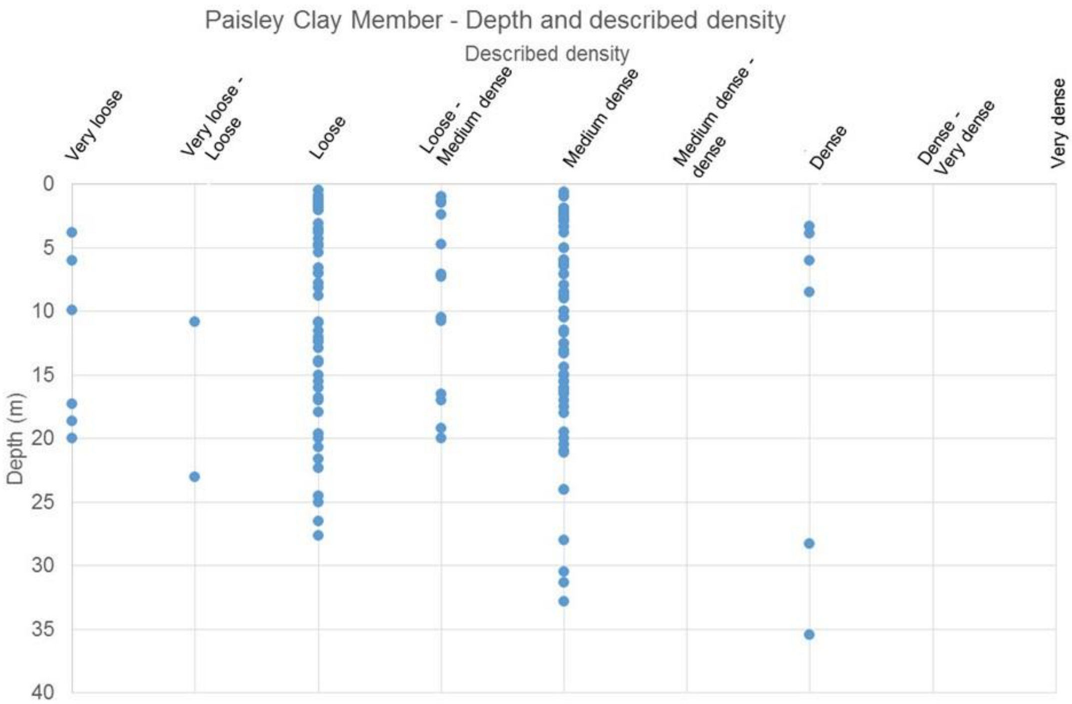

Killearn Sand and Gravel Member - Depth and described consistency
Described consistency
Very Soft
Very Soft - Soft
Soft
Soft - Firm
Firm
Firm - Stiff
Stiff
Stiff - Very stiff
Very stiff
Very stiff - Extremely weak
Depth (m)
0
1
2
3
4
5
6
7
8
9

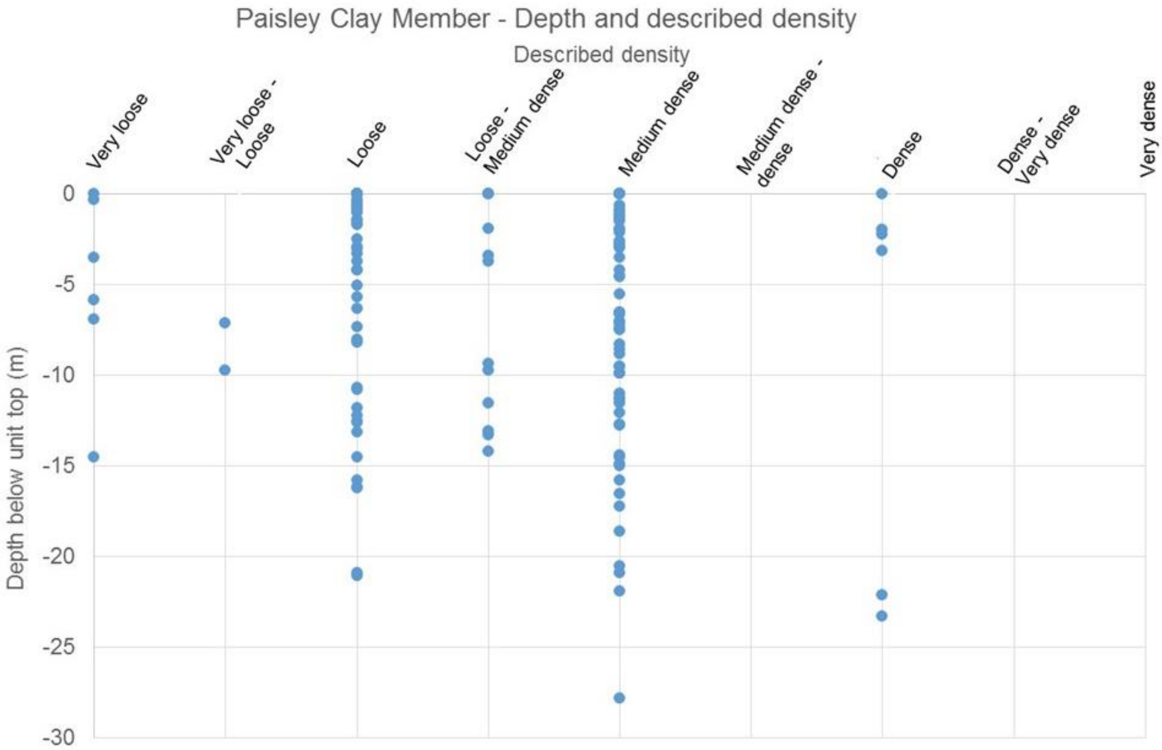

Killearn Sand and Gravel Member - Depth and described consistency
Described consistency
Very Soft
Very Soft - Soft
Soft
Soft - Firm
Firm
Firm - Stiff
Stiff
Stiff - Very stiff
Very stiff
Very stiff - Extremely weak
Depth below unit top (m)
0
-1
-2
-3
-4
-5
-6
-7
-8

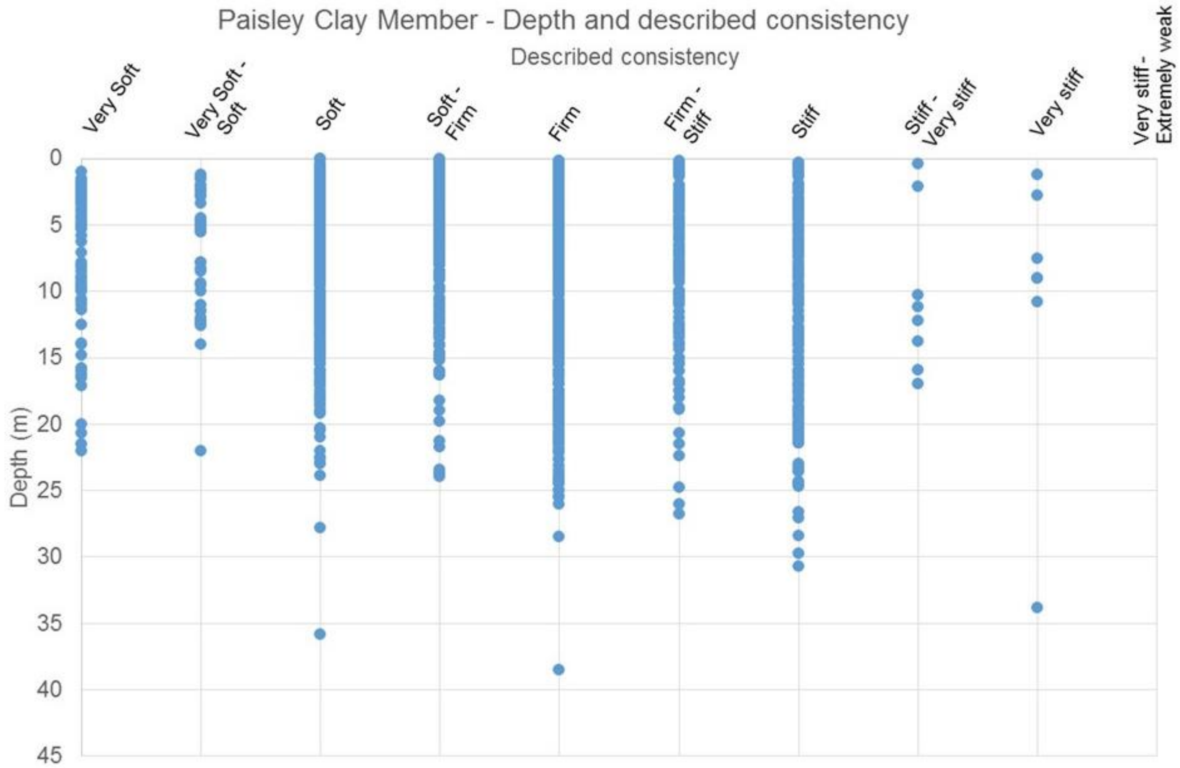

Killearn Sand and Gravel Member
Standard penetration test N-values (blows)
0
10
20
30
40
50
60
70
80
90
100
Depth (m)
0
2
4
6
8
10
12
14

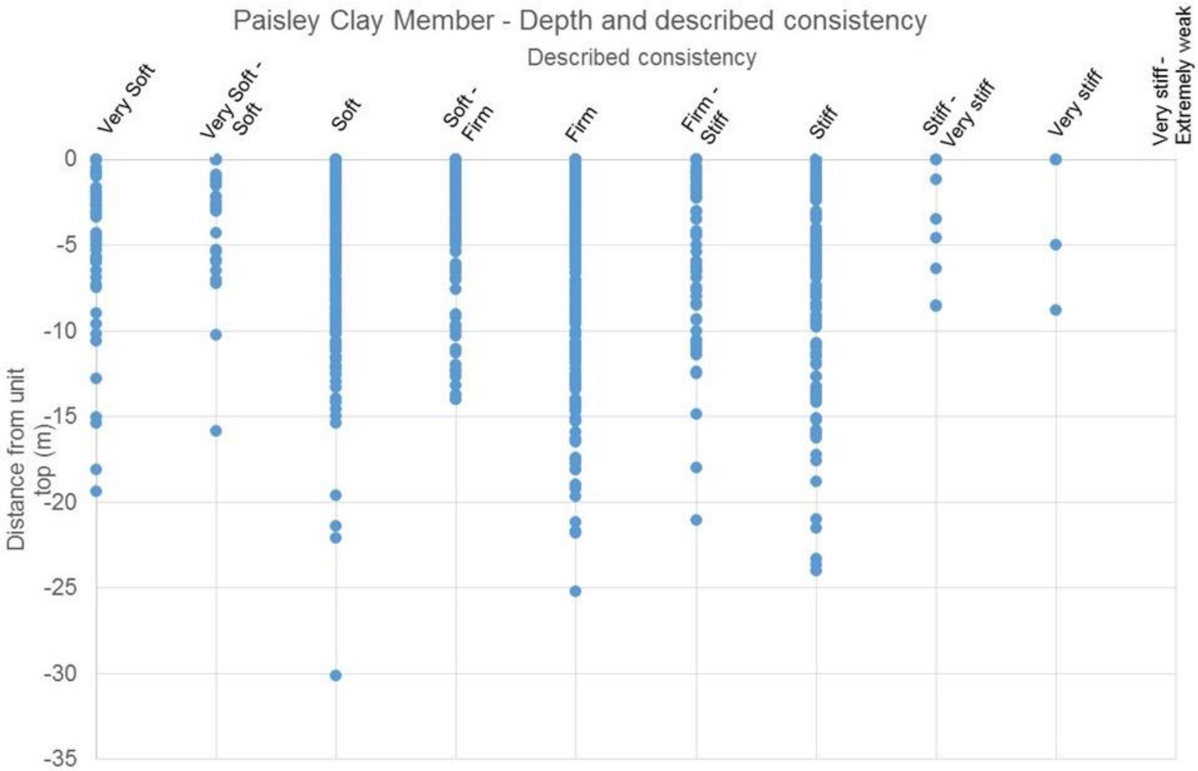

Particle size distribution - Killearn Sand and Gravel Member
50 samples
PERCENTAGE PASSING (%)
100
90
80
70
60
50
40
30
20
10
0
0.001
0.01
0.1
1
10
100
mm
Percentile
25 to 75
10 to 25
75 to 90
50
Minimum
Maximum
CLAY
Fine
Medium
Coarse
SILT
Fine
Medium
Coarse
SAND
Fine
Medium
Coarse
GRAVEL
COBBLES

Paisley Clay Member

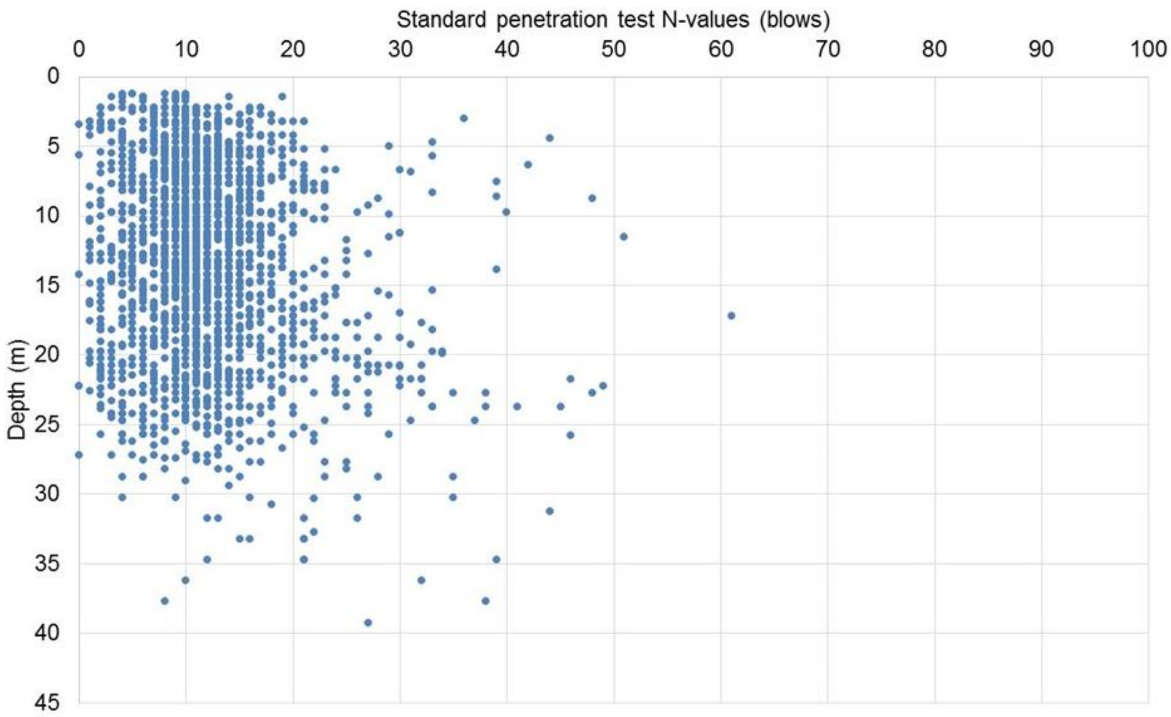




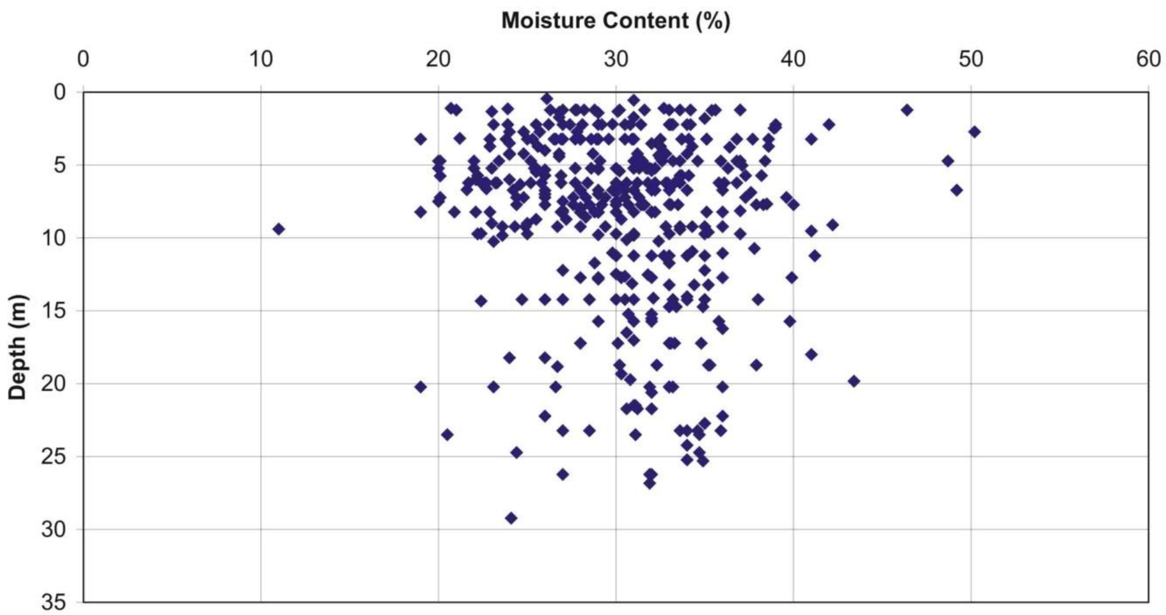

Paisley Clay Member - Depth and described consistency
Described consistency
Very Soft
Very Soft - Soft
Soft
Soft - Firm
Firm
Firm - Stiff
Stiff
Stiff - Very stiff
Very stiff
Very stiff - Extremely weak
Depth (m)
0
5
10
15
20
25
30
35
40
45

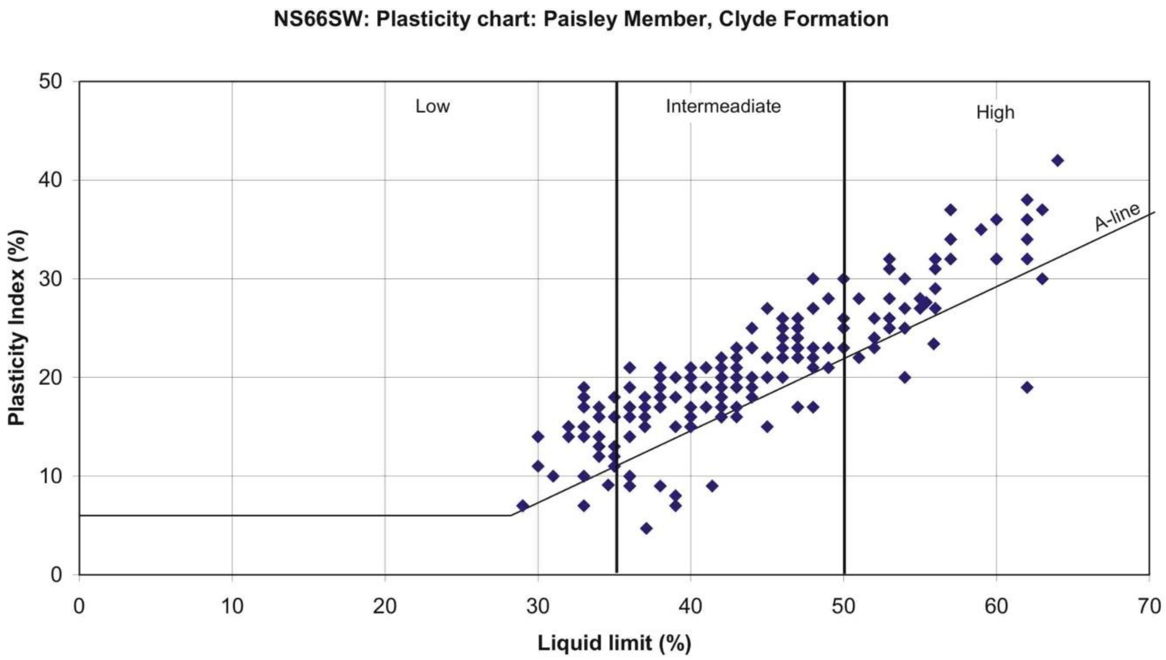

Paisley Clay Member - Depth and described consistency
Described consistency
Very Soft
Very Soft - Soft
Soft
Soft - Firm
Firm
Firm - Stiff
Stiff
Stiff - Very stiff
Very stiff
Very stiff - Extremely weak
Distance from unit top (m)
0
-5
-10
-15
-20
-25
-30
-35

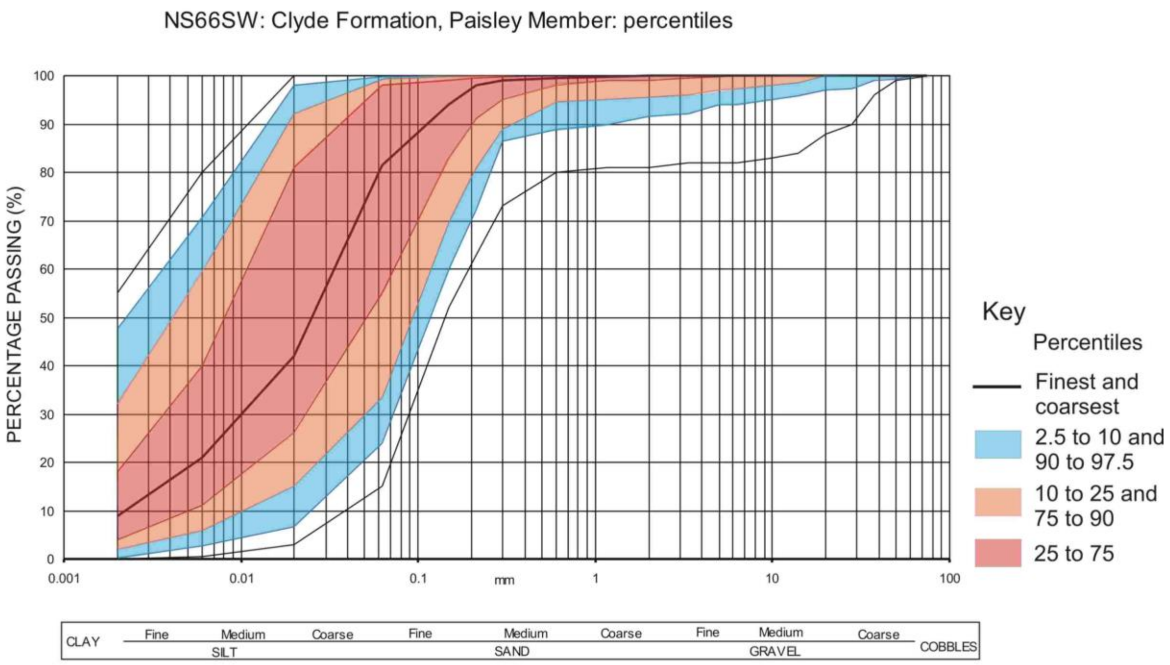
Paisley Clay Member

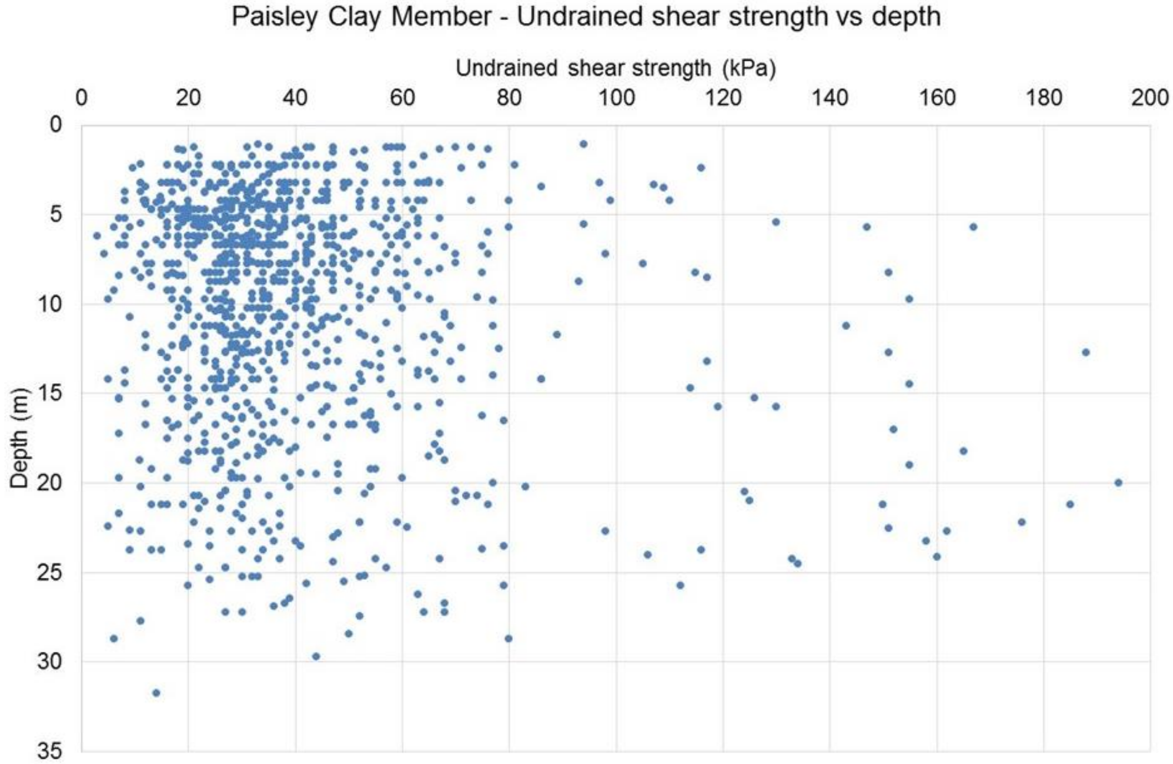


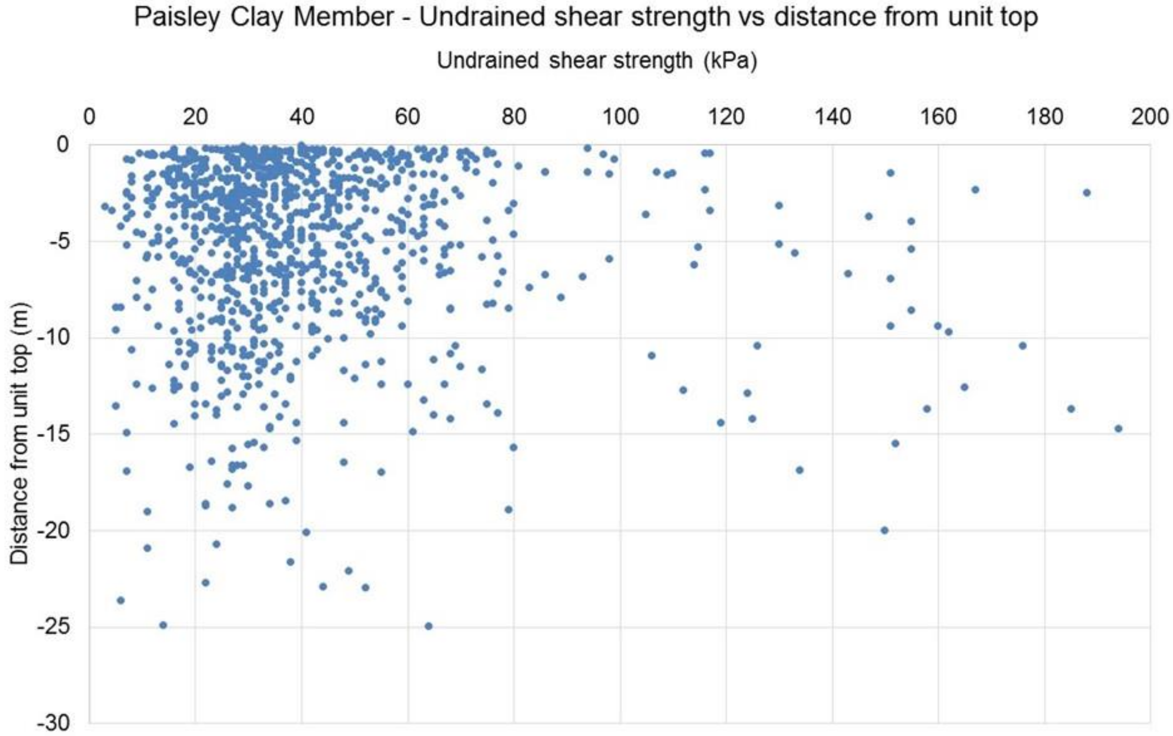
NS66SW: Moisture content profile: Clyde Formation, Paisley Member



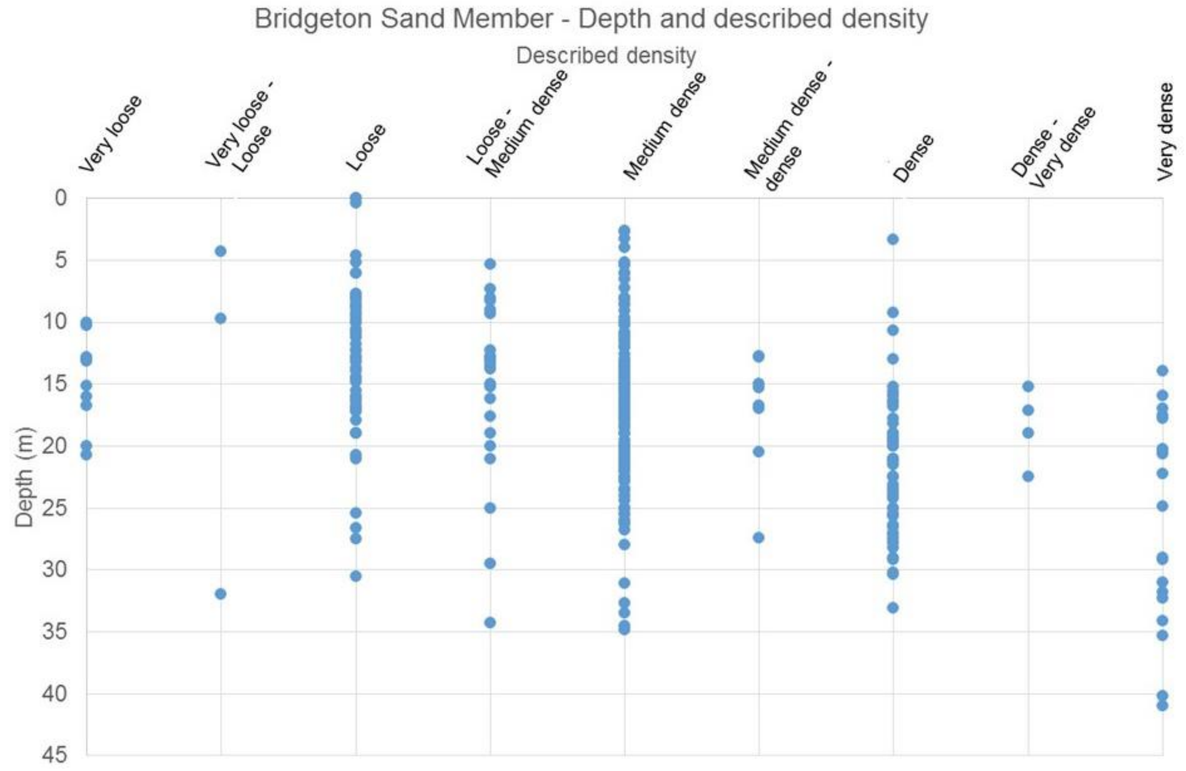

NS66SW: Plasticity chart: Paisley Member, Clyde Formation
Low
Intermeadiate
High
A-line
Plasticity Index (%)
Liquid limit (%)
0
10
20
30
40
50
60
70

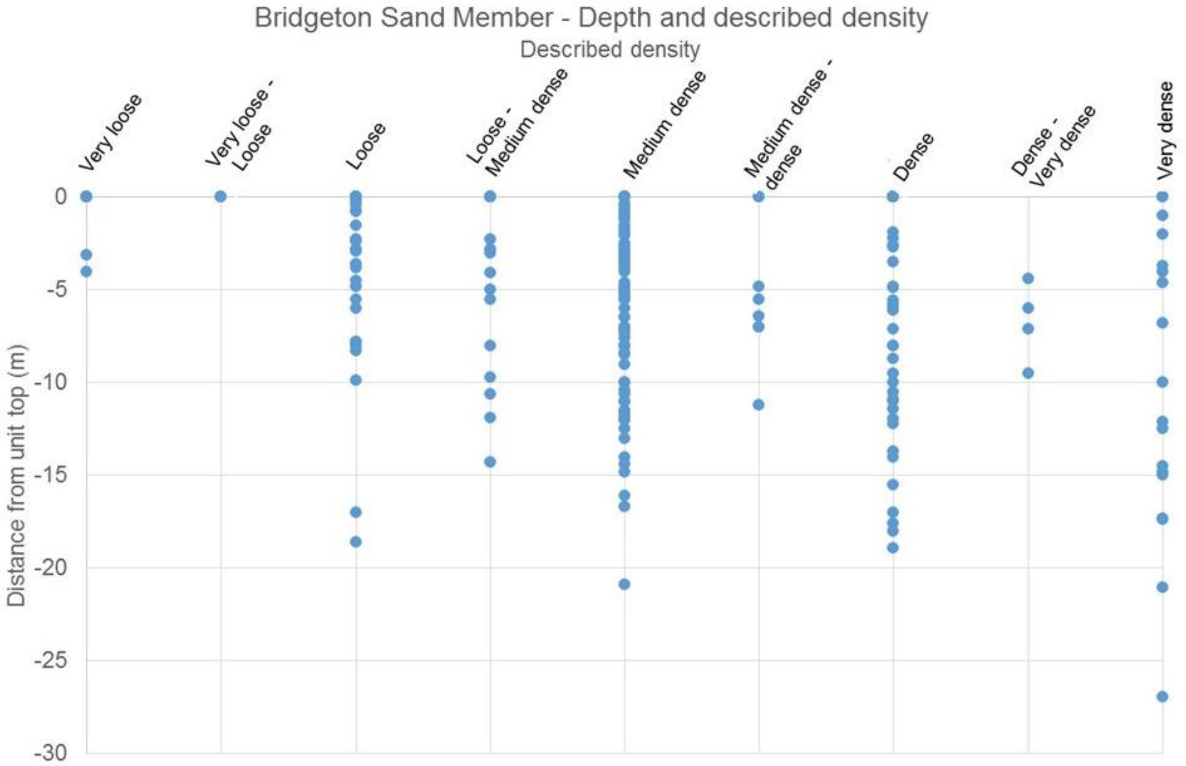

NS66SW: Clyde Formation, Paisley Member: percentiles
PERCENTAGE PASSING (%)
0.001
0.01
0.1
mm
1
10
100
CLAY
Fine
Medium
Coarse
SILT
SAND
GRAVEL
COBBLES
Key
Percentiles
Finest and coarsest
2.5 to 10 and 90 to 97.5
10 to 25 and 75 to 90
25 to 75

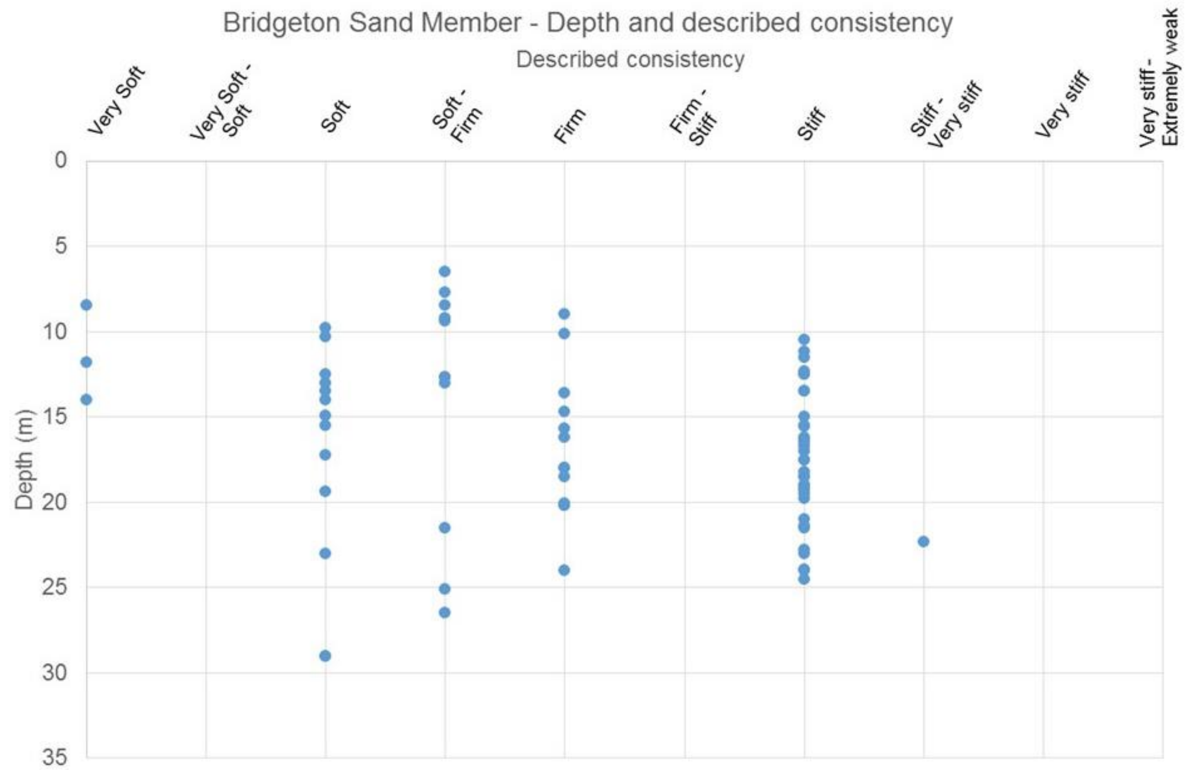

Paisley Clay Member - Undrained shear strength vs depth
Undrained shear strength (kPa)
0
20
40
60
80
100
120
140
160
180
200
Depth (m)
0
5
10
15
20
25
30
35

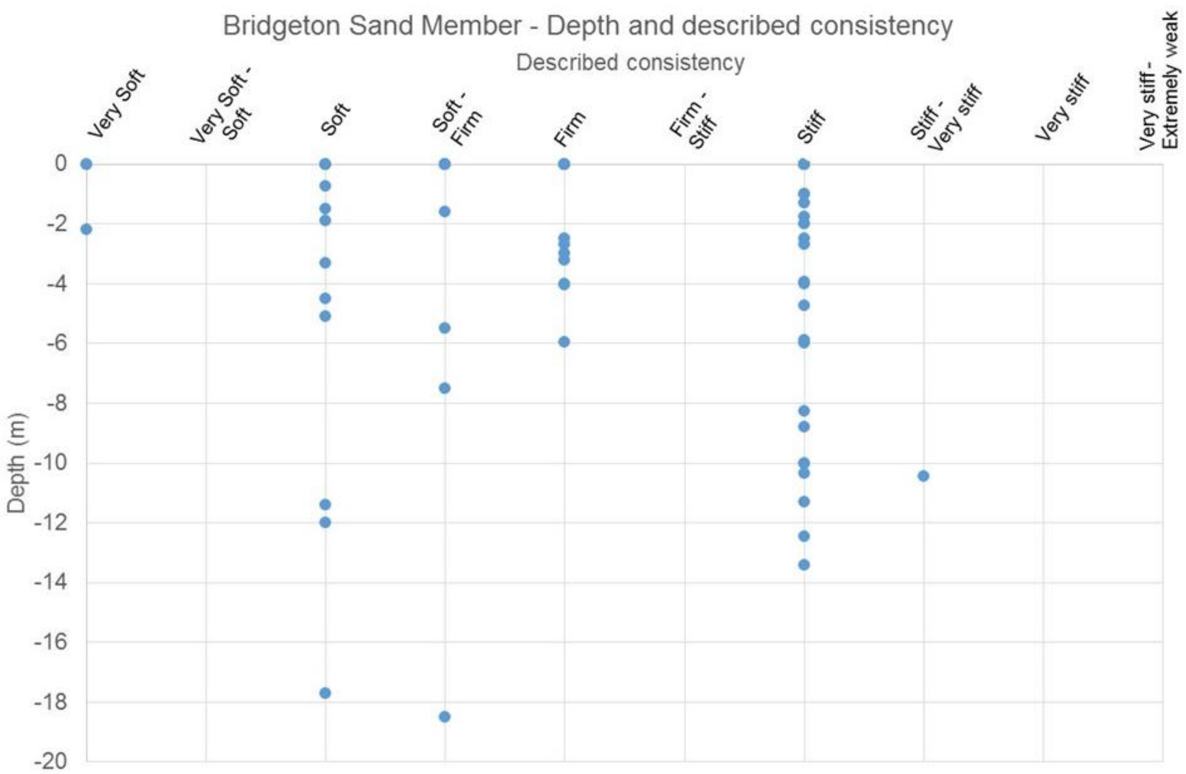

Paisley Clay Member - Undrained shear strength vs distance from unit top
Undrained shear strength (kPa)
0
20
40
60
80
100
120
140
160
180
200
Distance from unit top (m)
0
-5
-10
-15
-20
-25
-30

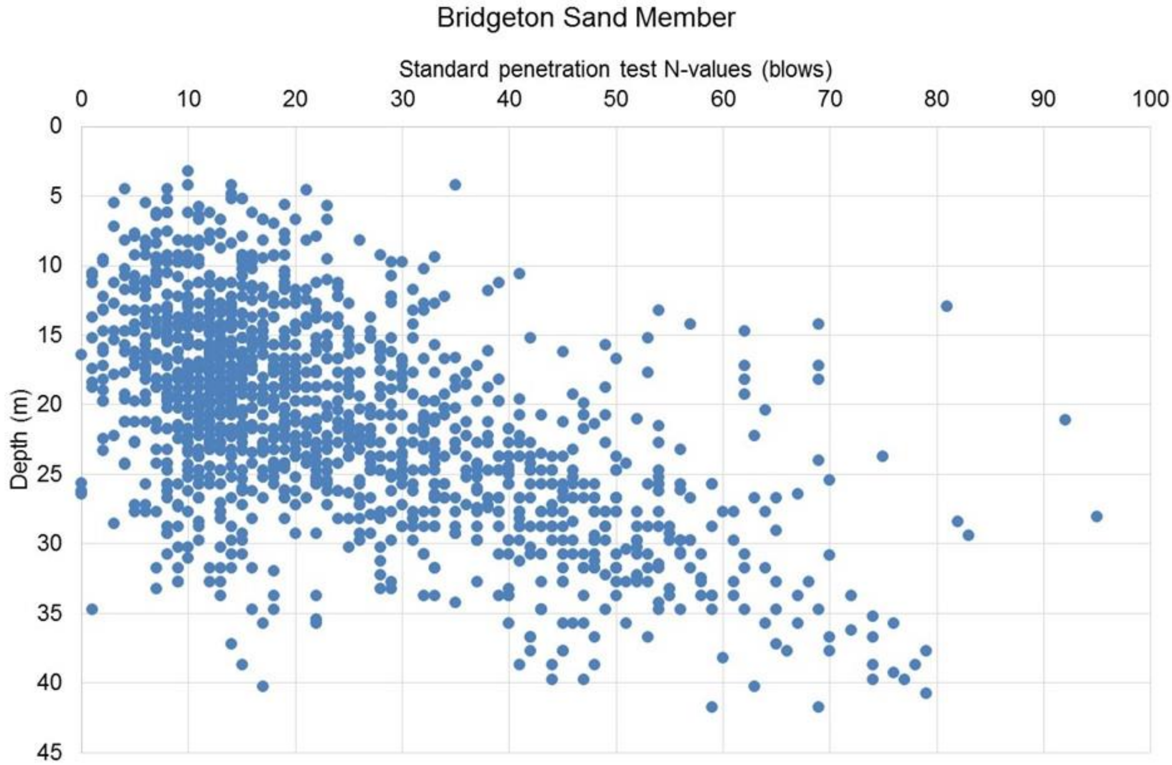
Bridgeton Sand Member

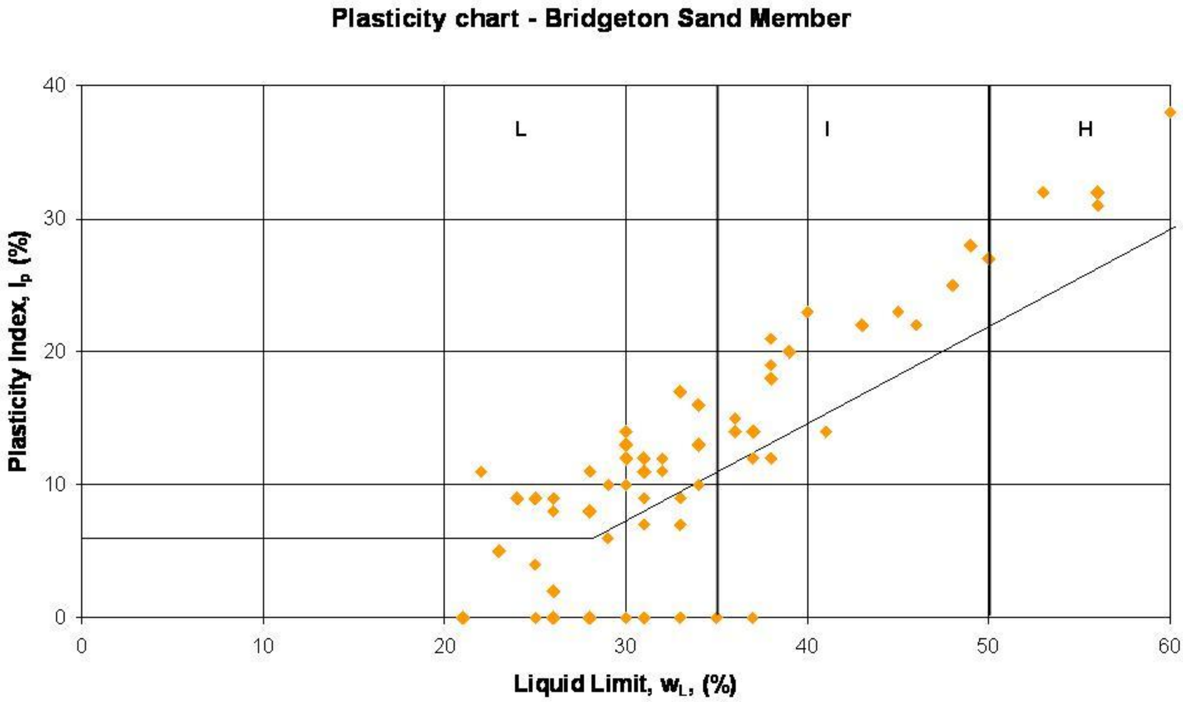




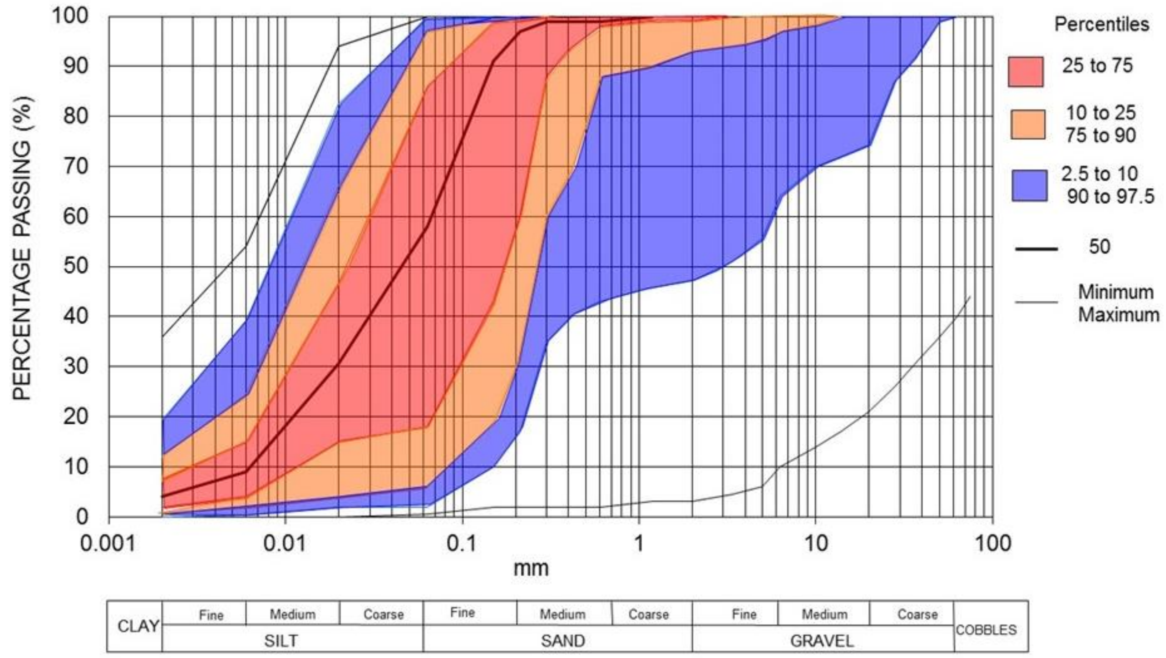

Bridgeton Sand Member - Depth and described consistency
Described consistency
Very Soft
Very Soft - Soft
Soft
Soft - Firm
Firm
Firm - Stiff
Stiff
Stiff - Very stiff
Very stiff
Very stiff - Extremely weak
Depth (m)
0
5
10
15
20
25
30
35


Bridgeton Sand Member - Depth and described consistency
Described consistency
Very Soft
Very Soft - Soft
Soft
Soft - Firm
Firm
Firm - Stiff
Stiff
Stiff - Very stiff
Very stiff
Very stiff - Extremely weak
Depth (m)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20

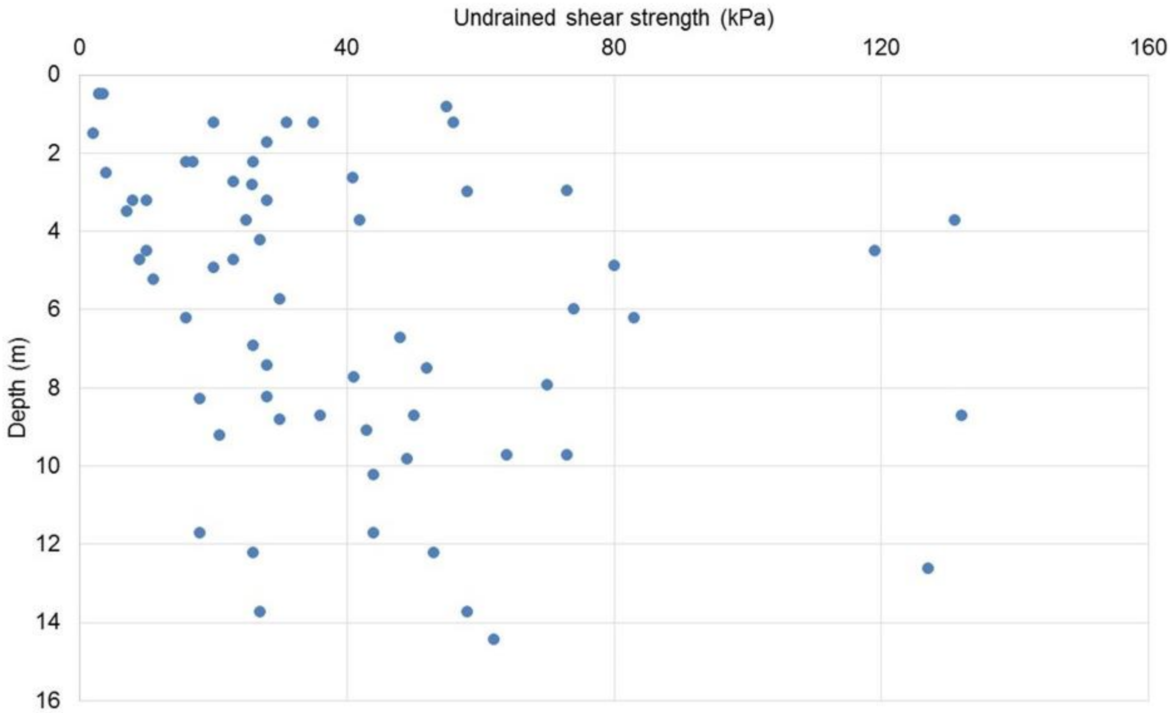

Bridgeton Sand Member
Standard penetration test N-values (blows)
0 10 20 30 40 50 60 70 80 90 100
0 5 10 15 20 25 30 35 40 45
Depth (m)

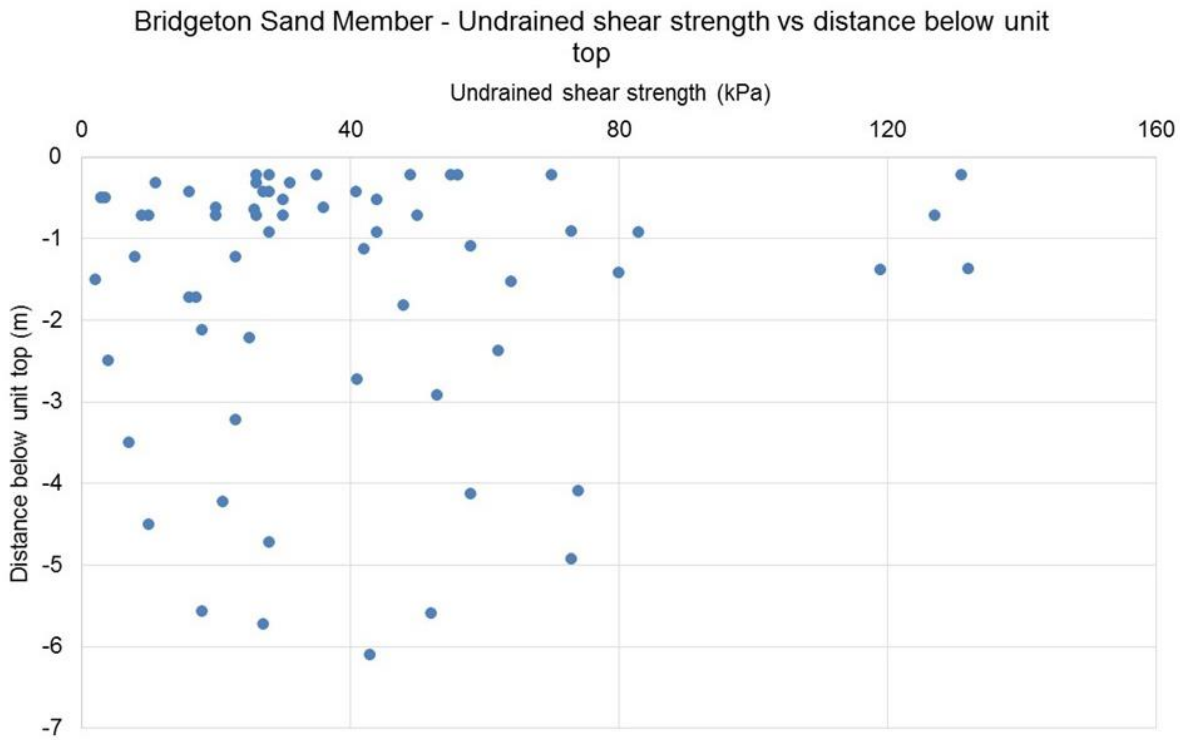

Plasticity chart - Bridgeton Sand Member
L
I
H
Plasticity Index, I_p (%)
0 10 20 30 40
0 10 20 30 40 50 60
Liquid Limit, w_L, (%)

Particle size distribution - Bridgeton Sand Member Gateway
280 samples

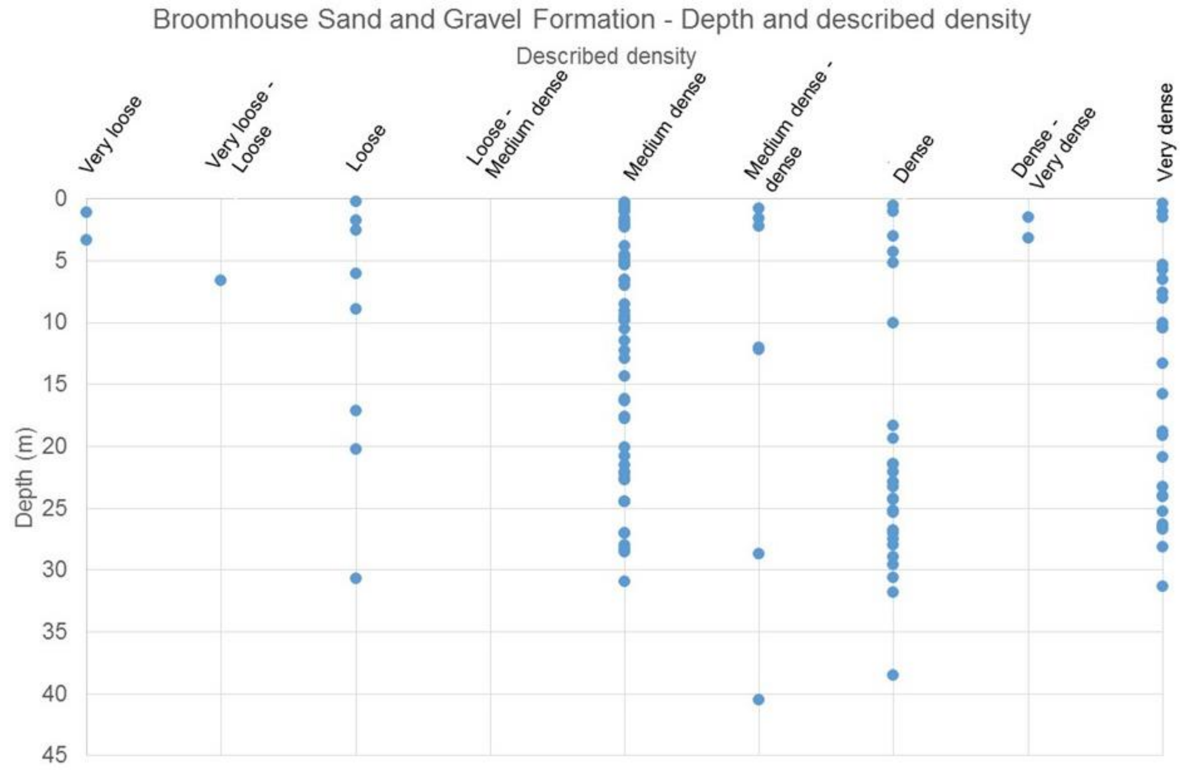


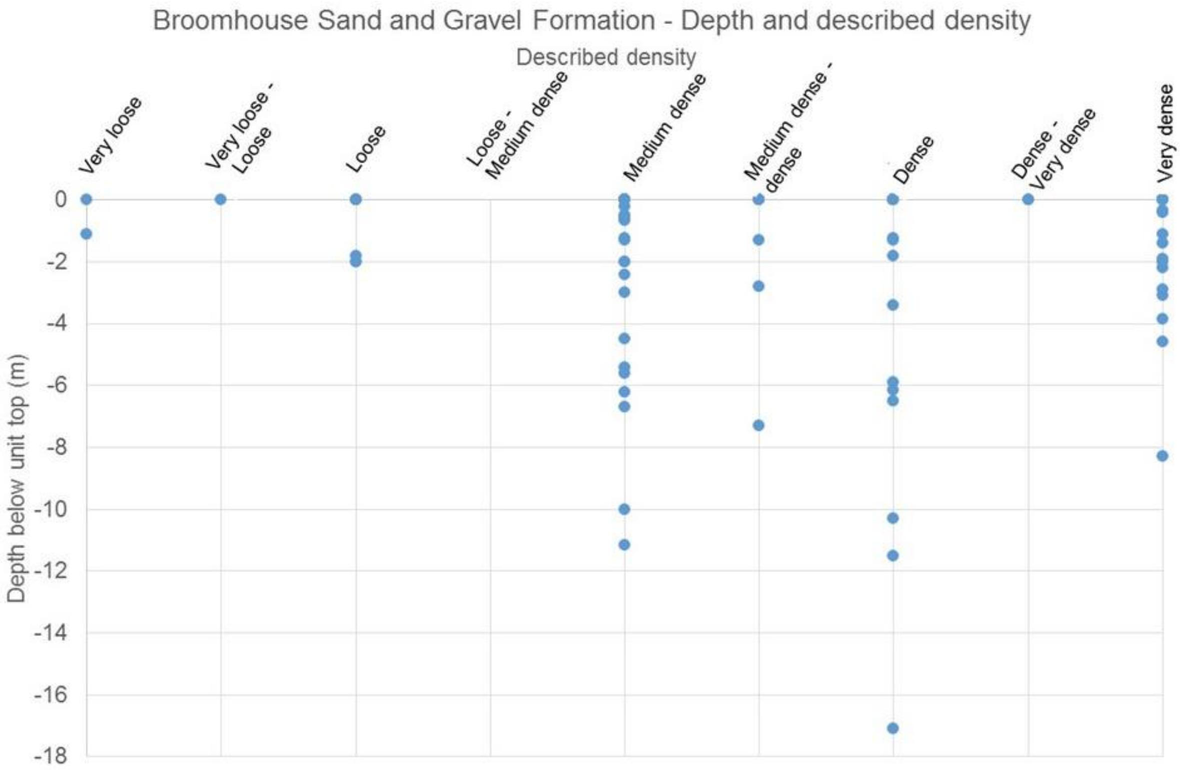
Bridgeton Sand Member - Undrained shear strength vs depth

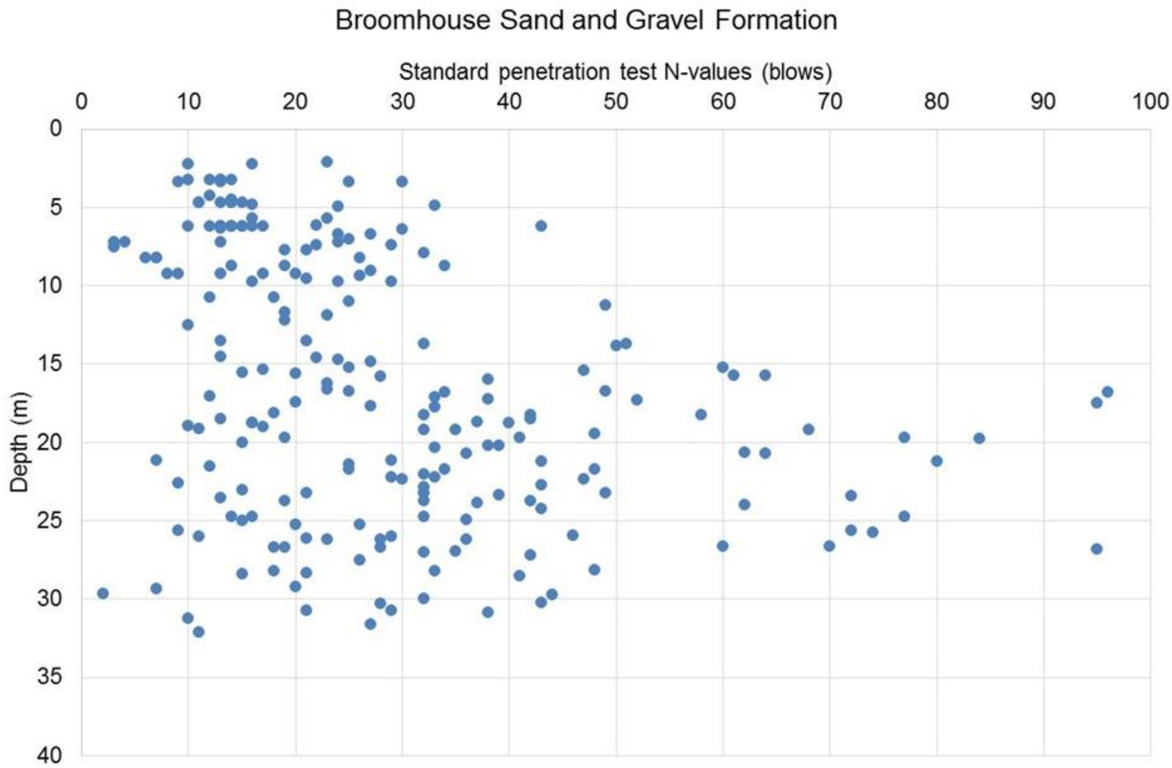


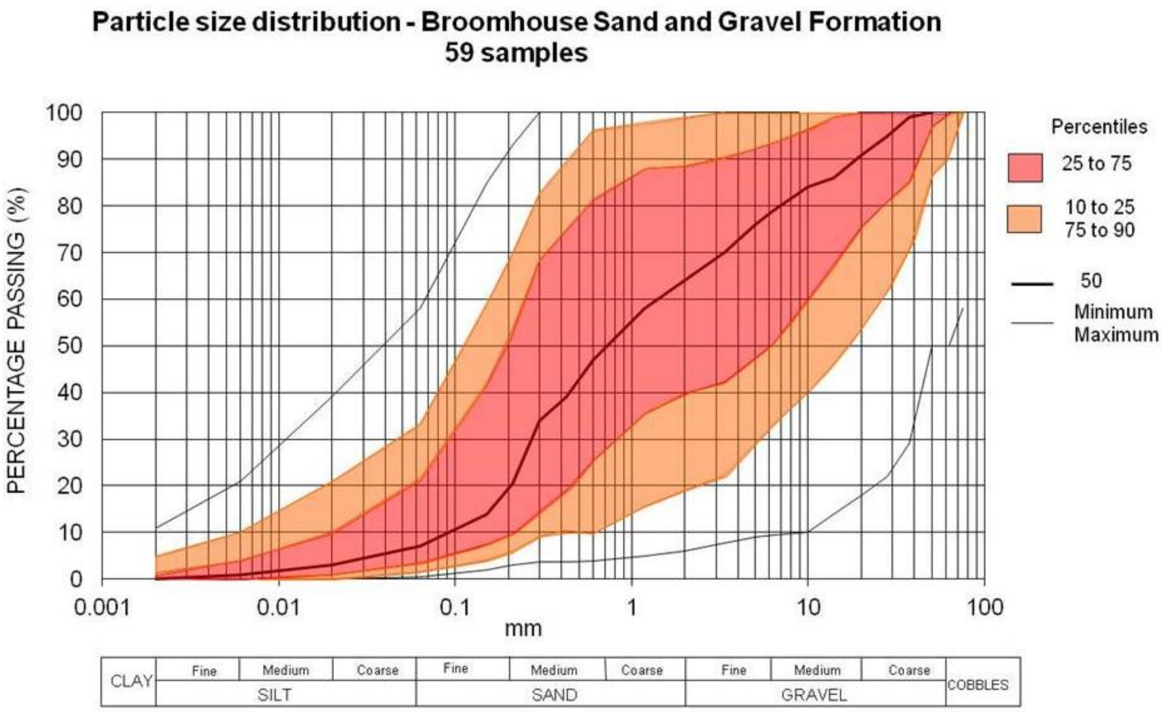

Bridgeton Sand Member - Undrained shear strength vs distance below unit top
Undrained shear strength (kPa)
0
40
80
120
160
Distance below unit top (m)
0
-1
-2
-3
-4
-5
-6
-7

Broomhouse Sand and Gravel Formation (including clay facies) unclassified

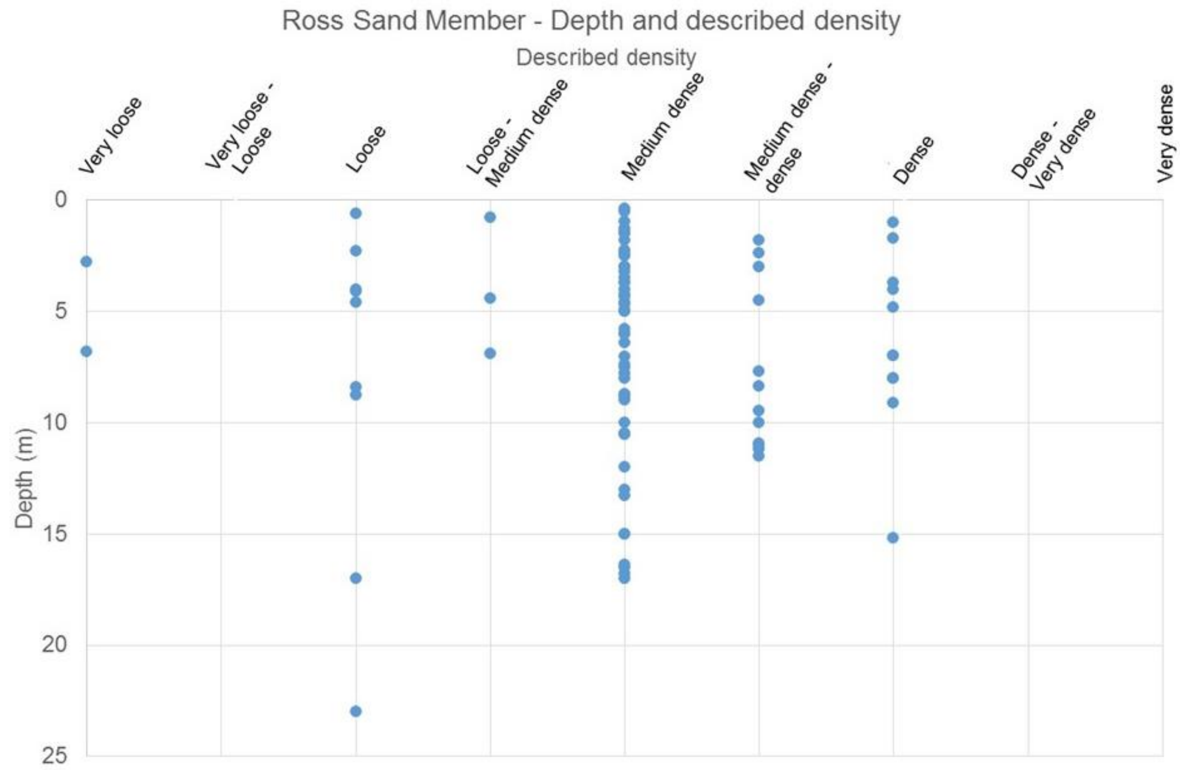


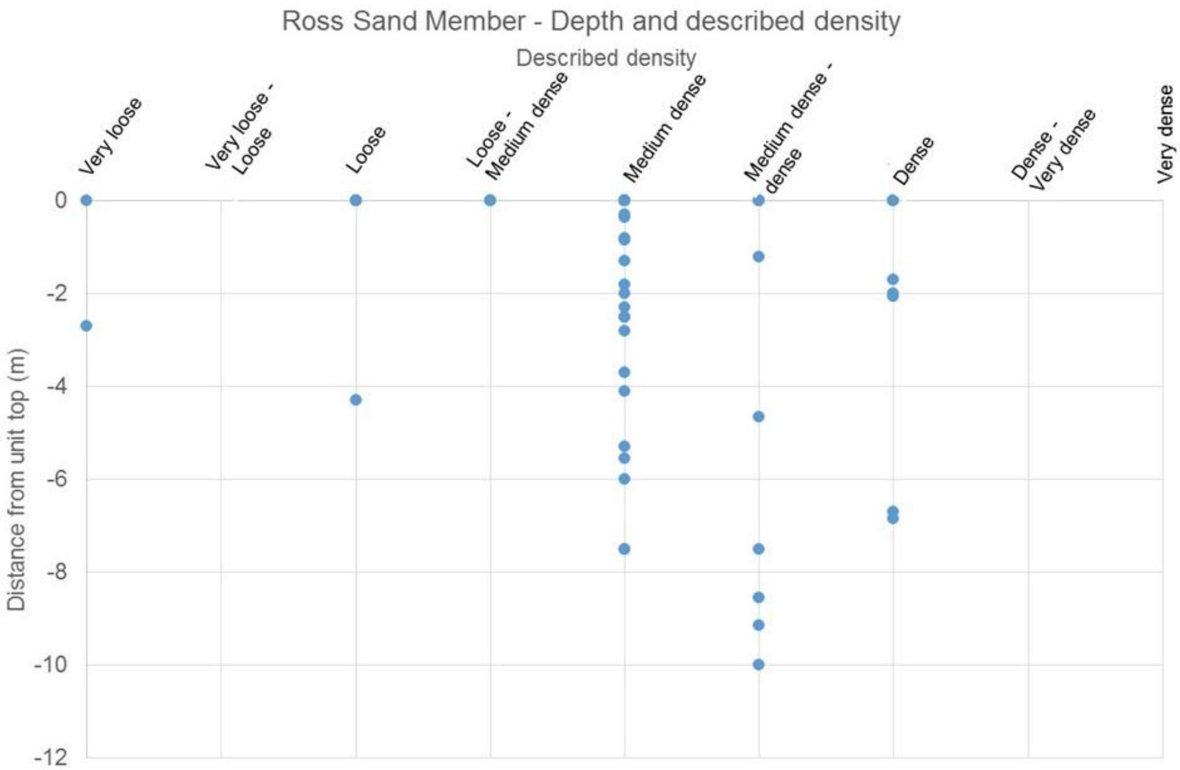


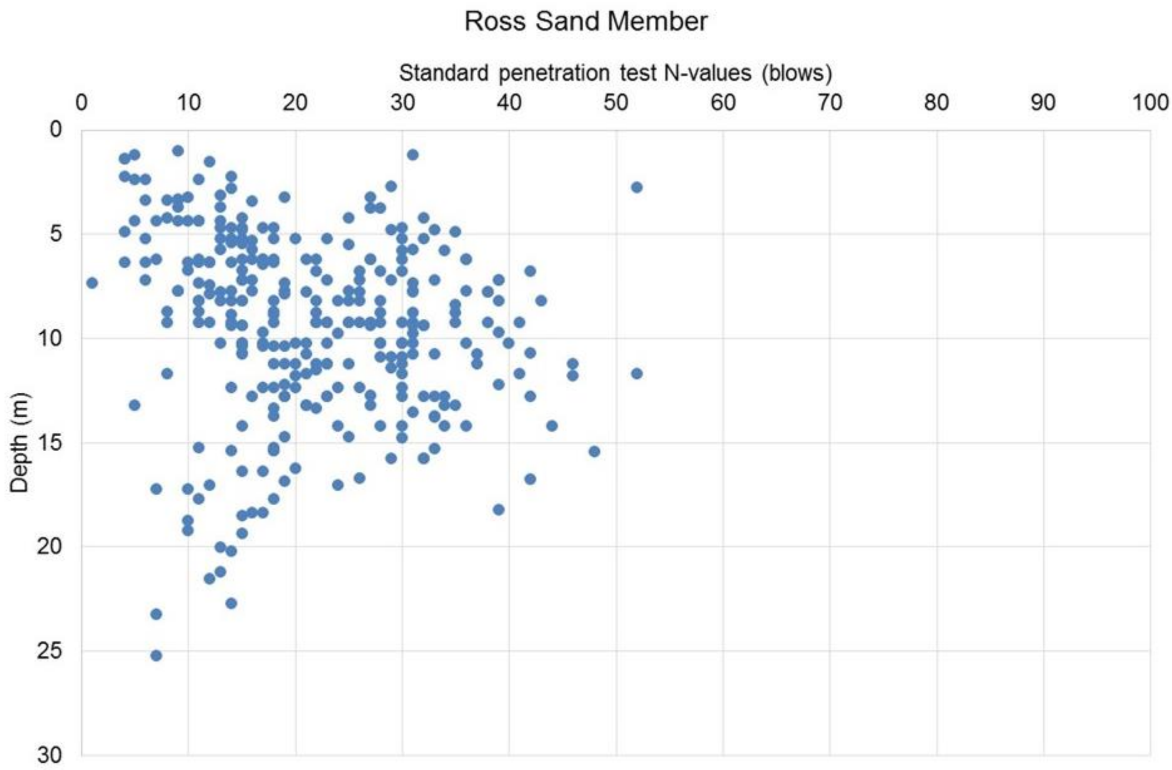

Broomhouse Sand and Gravel Formation
Standard penetration test N-values (blows)
Depth (m)

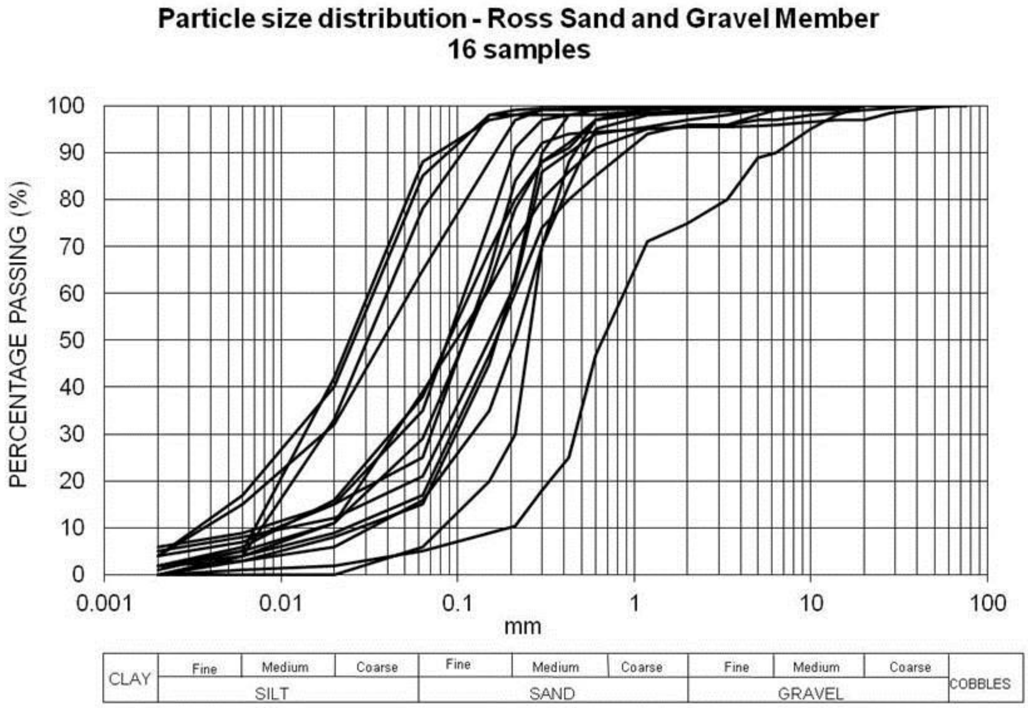

Particle size distribution - Broomhouse Sand and Gravel Formation
59 samples
PERCENTAGE PASSING (%)
mm
Percentiles
25 to 75
10 to 25
75 to 90
50
Minimum
Maximum
CLAY
Fine
Medium
Coarse
SILT
SAND
GRAVEL
COBBLES

Ross Sand Member

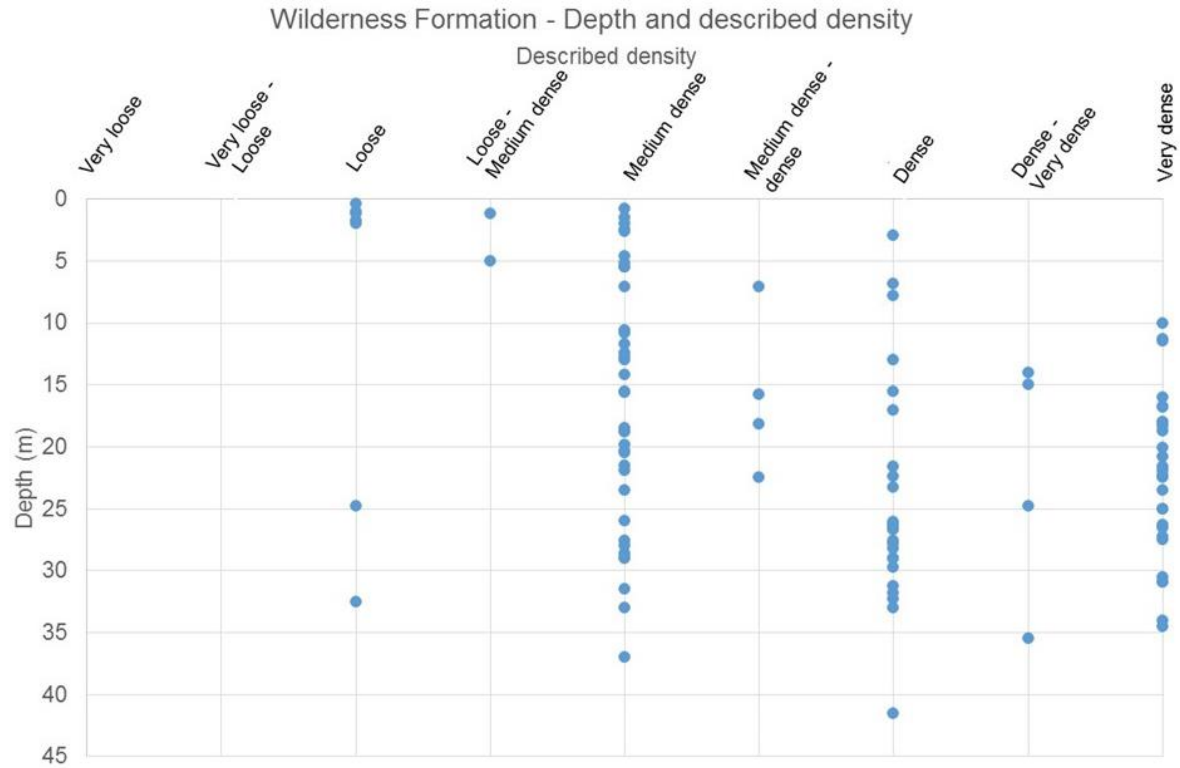


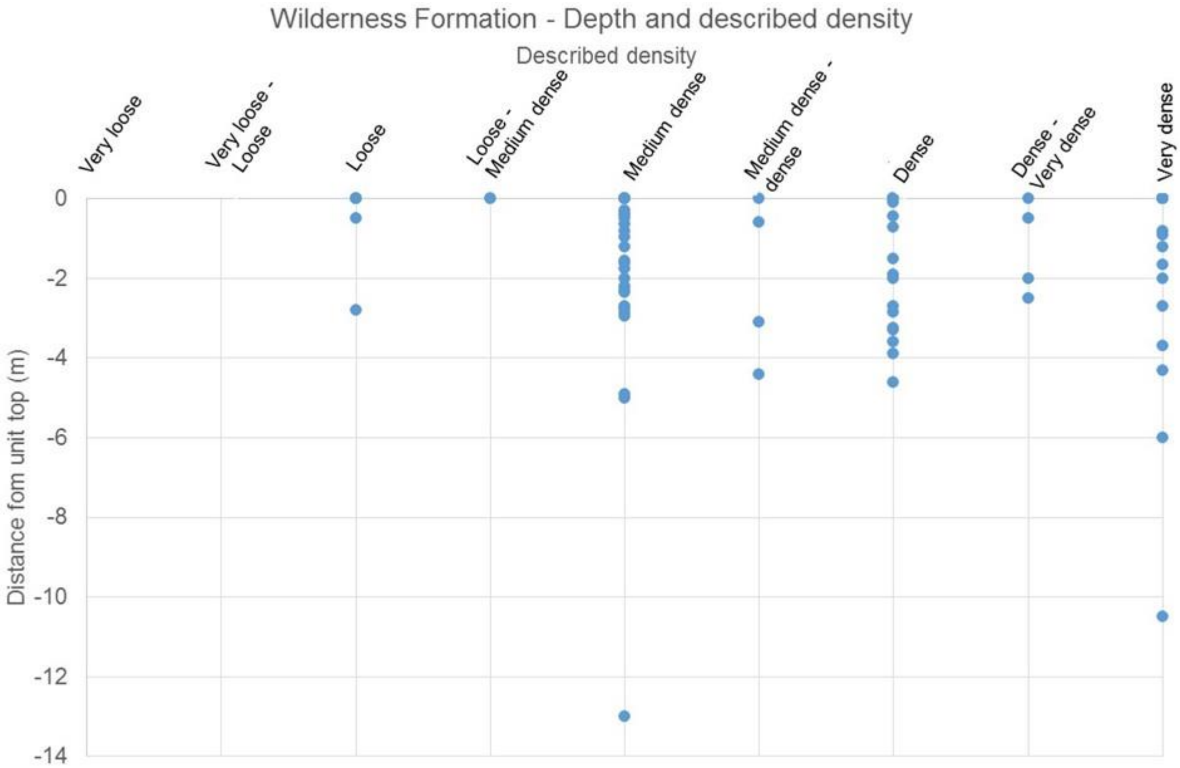


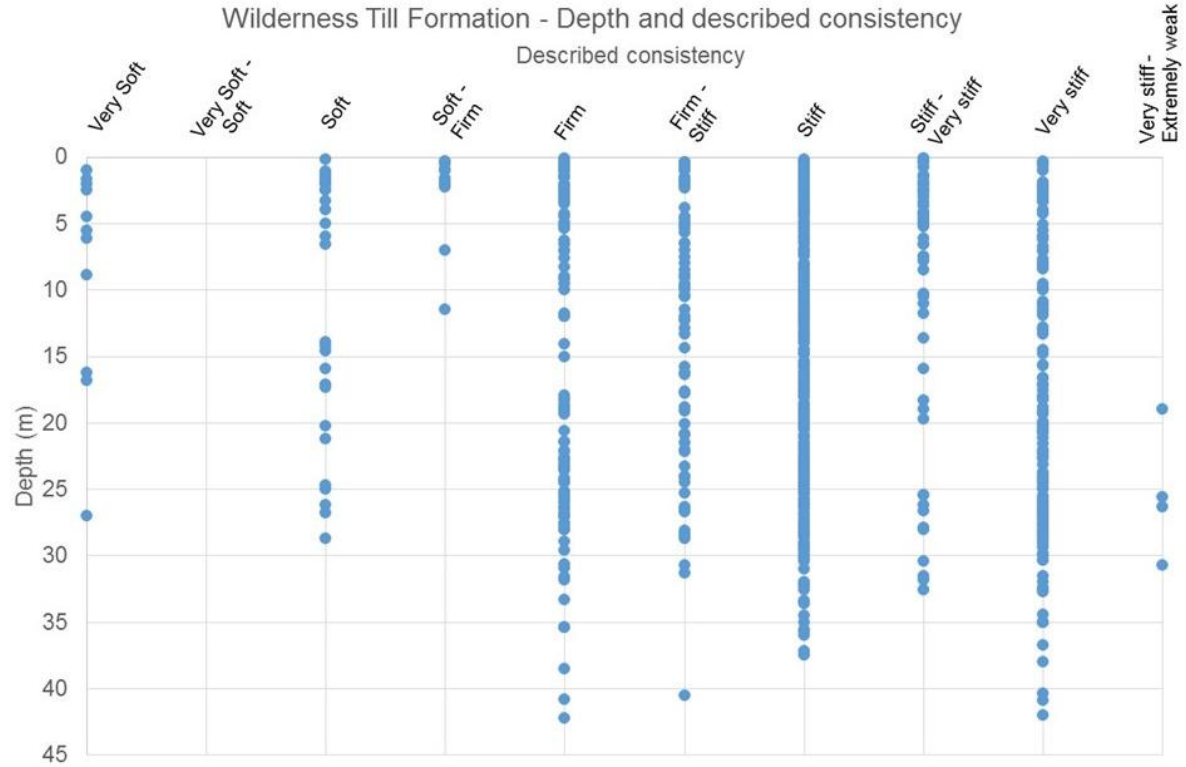

Ross Sand Member
Standard penetration test N-values (blows)
Depth (m)

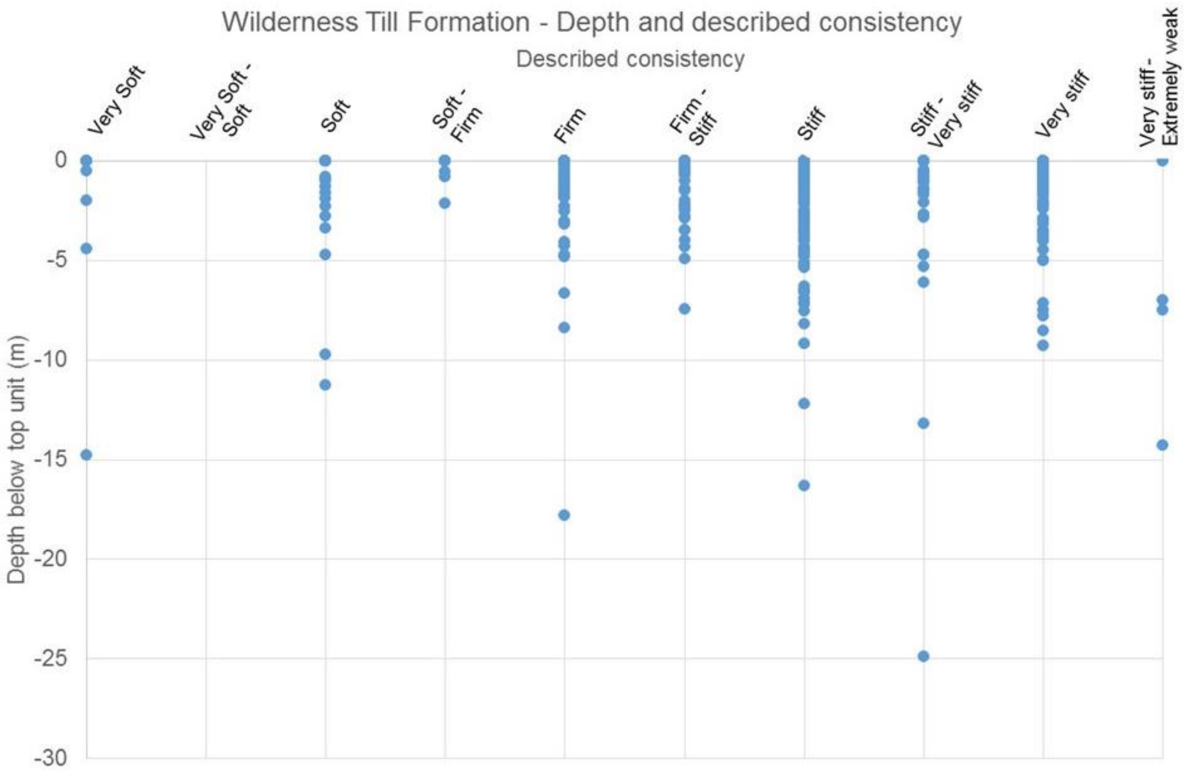

Particle size distribution - Ross Sand and Gravel Member
16 samples
PERCENTAGE PASSING (%)
mm
CLAY
Fine
Medium
Coarse
SILT
SAND
GRAVEL
COBBLES

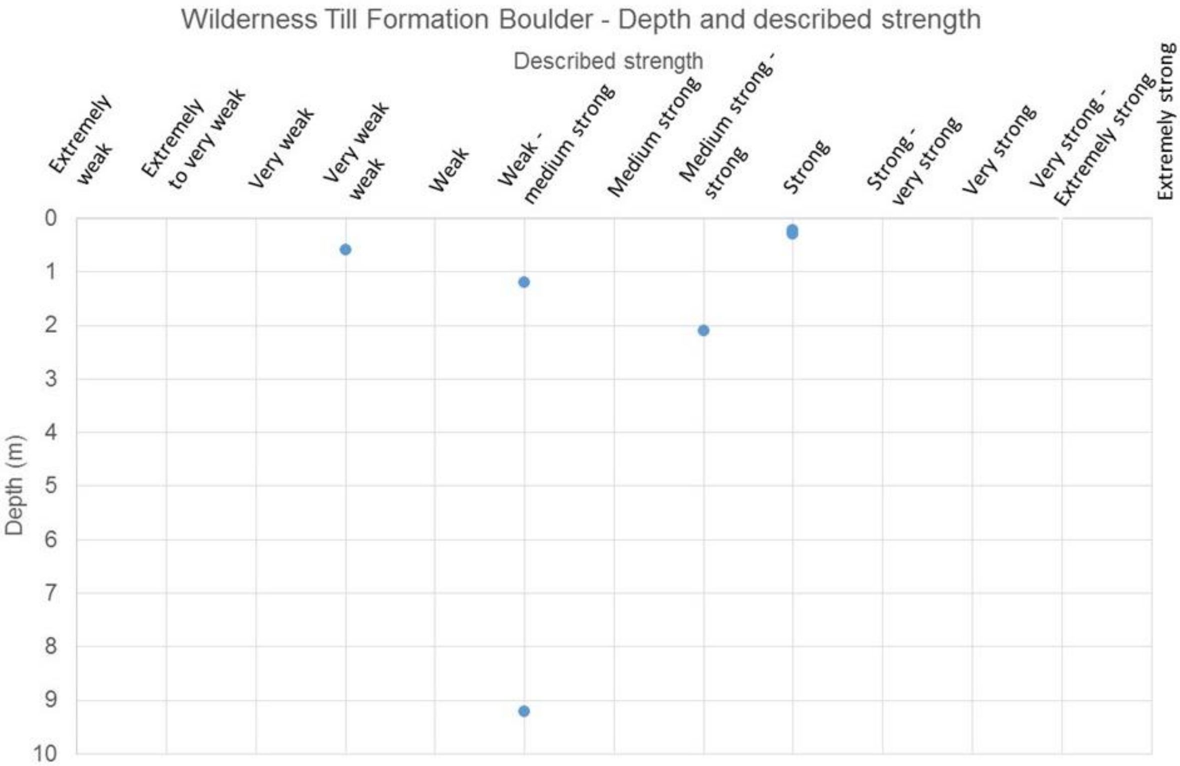
Wilderness Till Formation

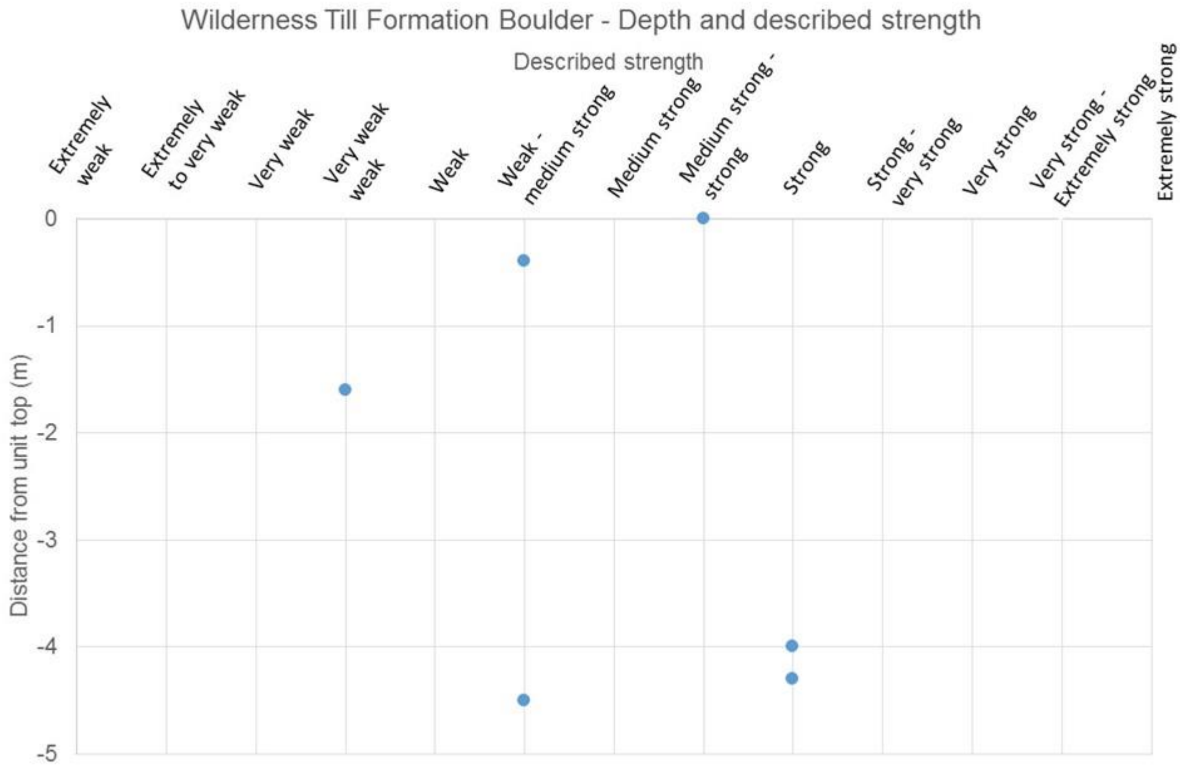


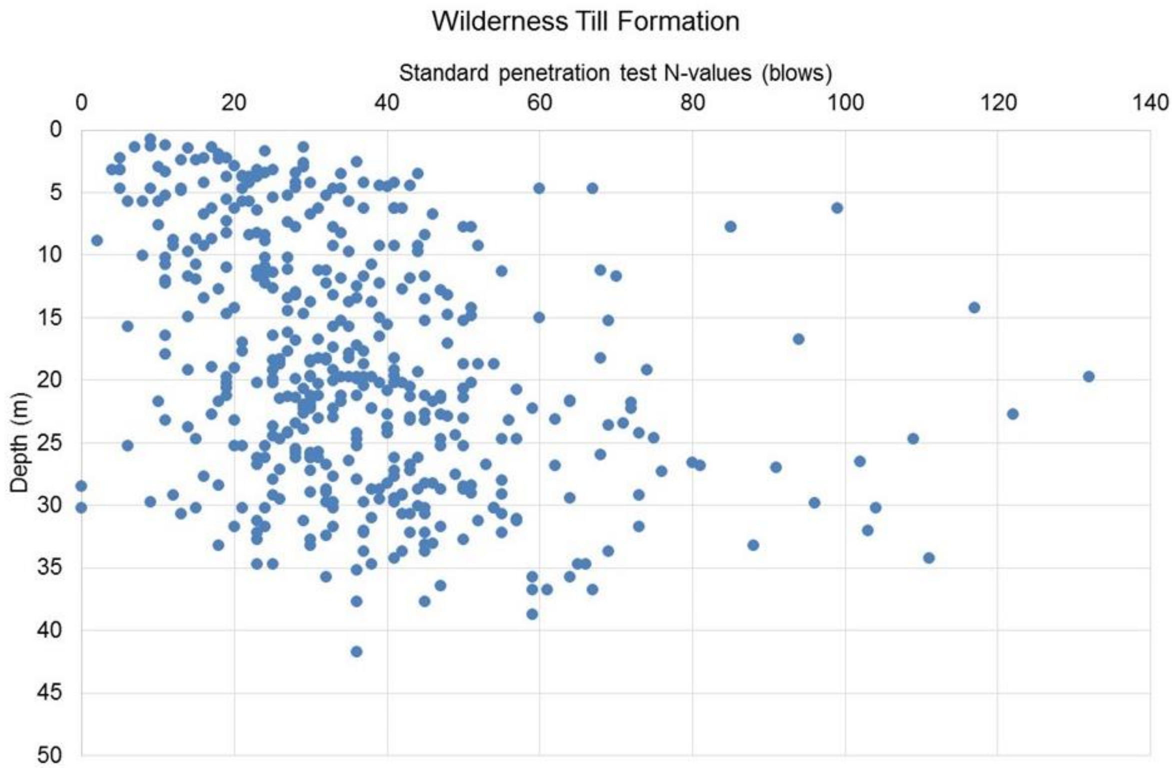


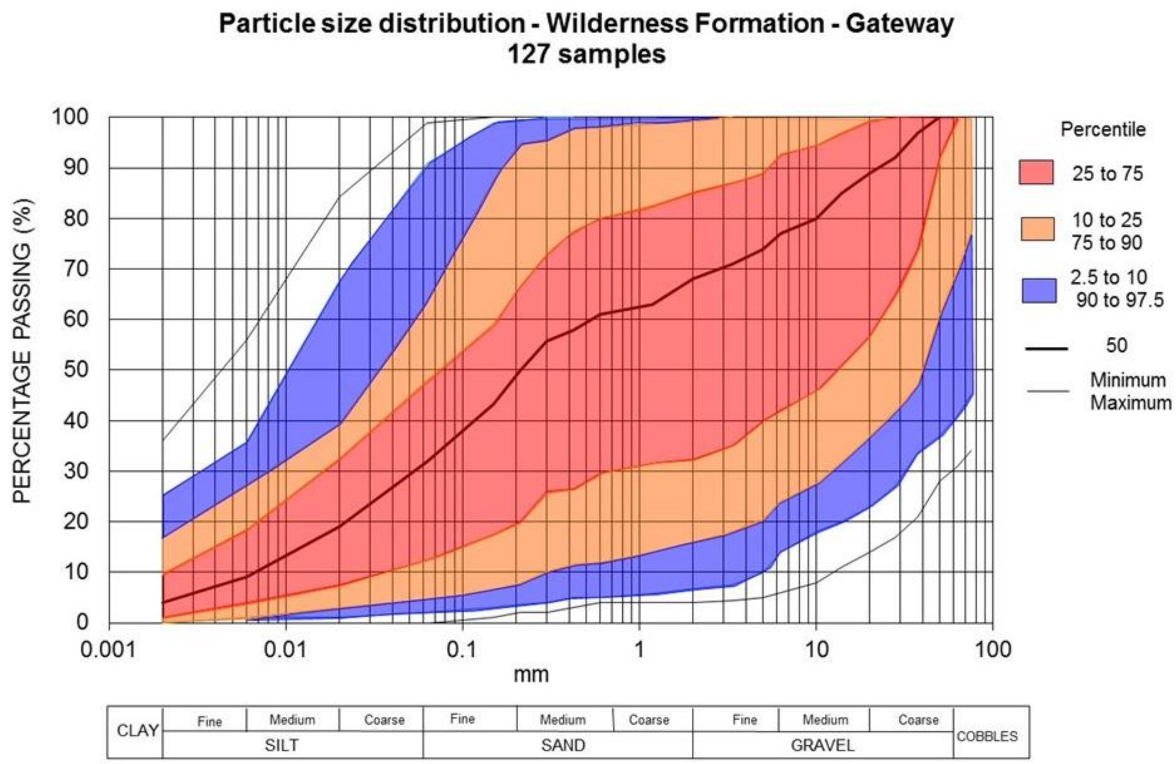

Wilderness Till Formation - Depth and described consistency
Described consistency
Very Soft
Very Soft - Soft
Soft
Soft - Firm
Firm
Firm - Stiff
Stiff
Stiff - Very stiff
Very stiff
Very stiff - Extremely weak
Depth (m)
0
5
10
15
20
25
30
35
40
45


Wilderness Till Formation - Depth and described consistency
Described consistency
Very Soft
Very Soft - Soft
Soft
Soft - Firm
Firm
Firm - Stiff
Stiff
Stiff - Very stiff
Very stiff
Very stiff - Extremely weak
Depth below top unit (m)
0
-5
-10
-15
-20
-25
-30

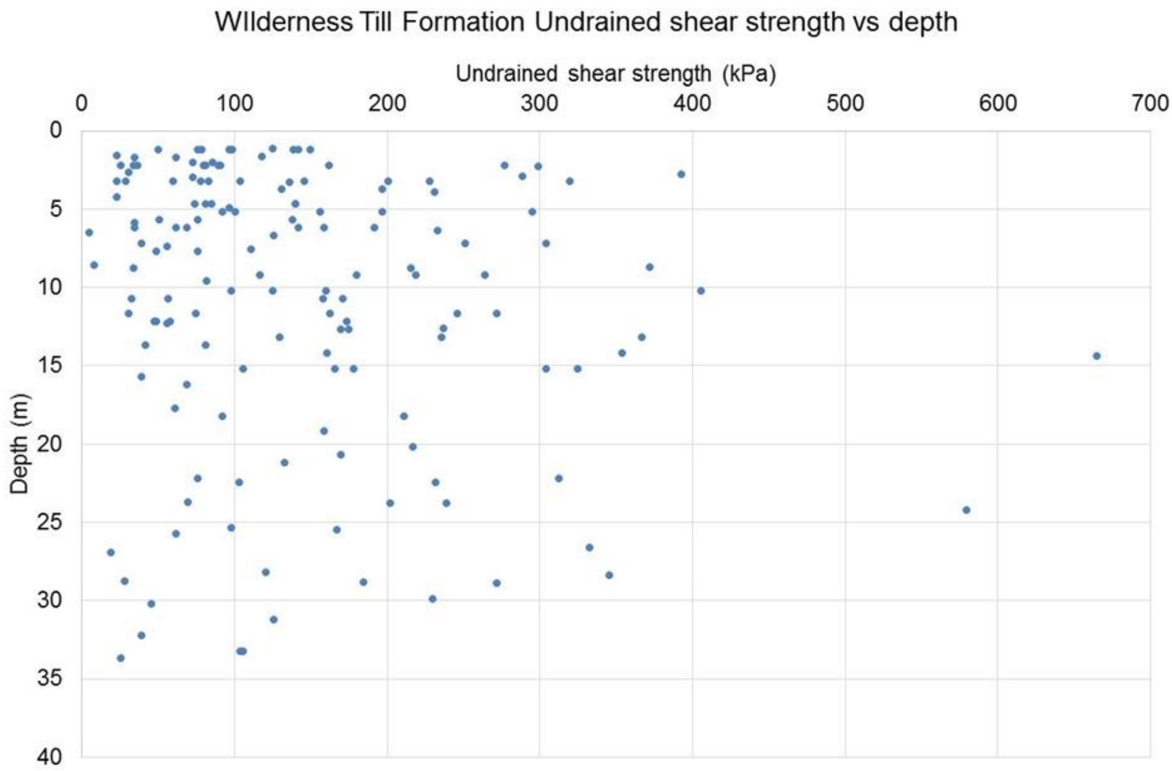

Wilderness Till Formation Boulder - Depth and described strength
Described strength
Extremely weak
Extremely to very weak
Very weak
Very weak weak
Weak
Weak - medium strong
Medium strong
Medium strong - strong
Strong
Strong - very strong
Very strong
Very strong - Extremely strong
Extremely strong
Depth (m)
0
1
2
3
4
5
6
7
8
9
10

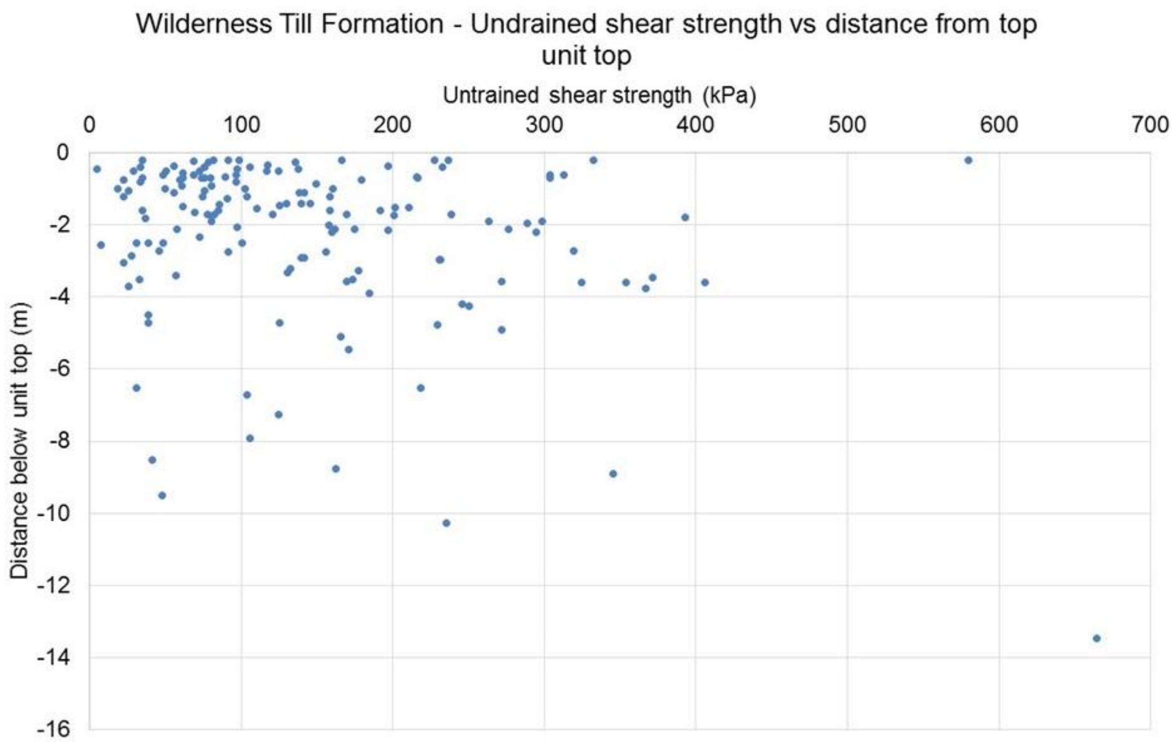

Wilderness Till Formation Boulder - Depth and described strength
Described strength
Extremely weak
Extremely to very weak
Very weak
Very weak weak
Weak
Weak - medium strong
Medium strong
Medium strong - strong
Strong
Strong - very strong
Very strong
Very strong - Extremely strong
Extremely strong
Distance from unit top (m)
0
-1
-2
-3
-4
-5


Wilderness Till Formation
Standard penetration test N-values (blows)
0
20
40
60
80
100
120
140
0
5
10
15
20
25
30
35
40
45
50
Depth (m)


Particle size distribution - Wilderness Formation - Gateway
127 samples
PERCENTAGE PASSING (%)
100
90
80
70
60
50
40
30
20
10
0
0.001
0.01
0.1
1
10
100
mm
Percentile
25 to 75
10 to 25
75 to 90
2.5 to 10
90 to 97.5
50
Minimum
Maximum
CLAY
Fine
Medium
Coarse
SILT
Fine
Medium
Coarse
SAND
Fine
Medium
Coarse
GRAVEL
COBBLES


Wilderness Till Formation
Water Content (%)
0
5
10
15
20
25
30
35
40
45
Depth (m)
0
5
10
15
20
25
30
35
40
45

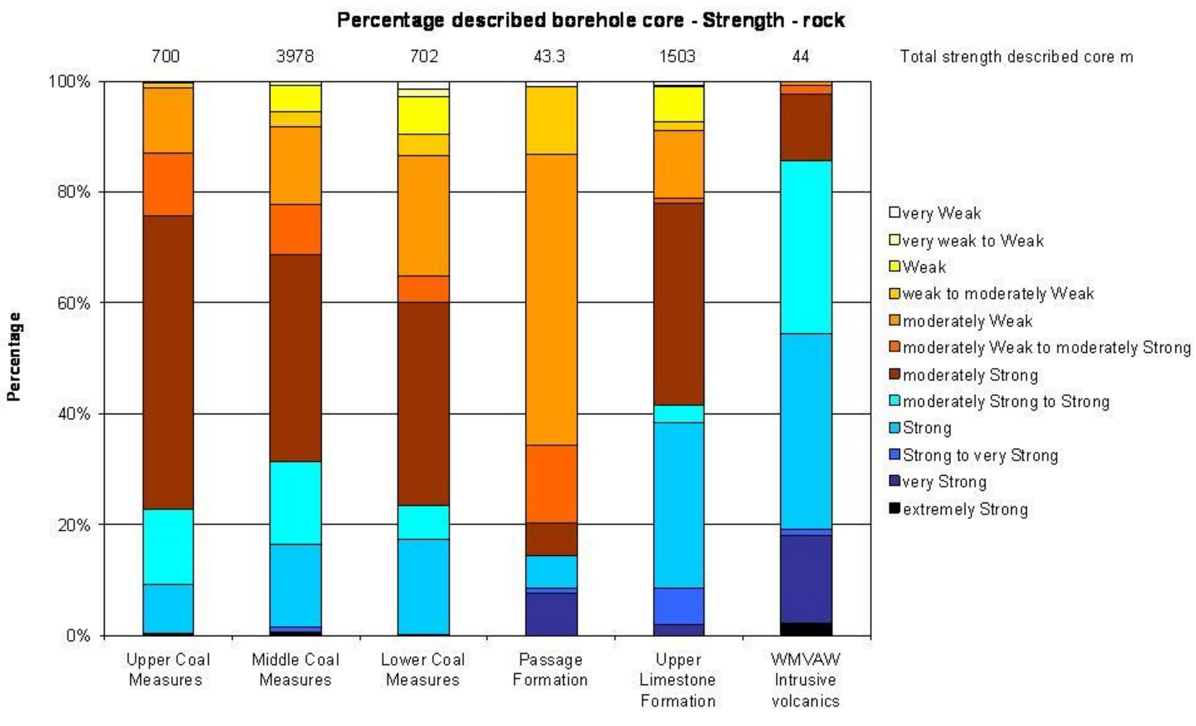

WIlderness Till Formation Undrained shear strength vs depth
Undrained shear strength (kPa)
0
100
200
300
400
500
600
700
Depth (m)
0
5
10
15
20
25
30
35
40

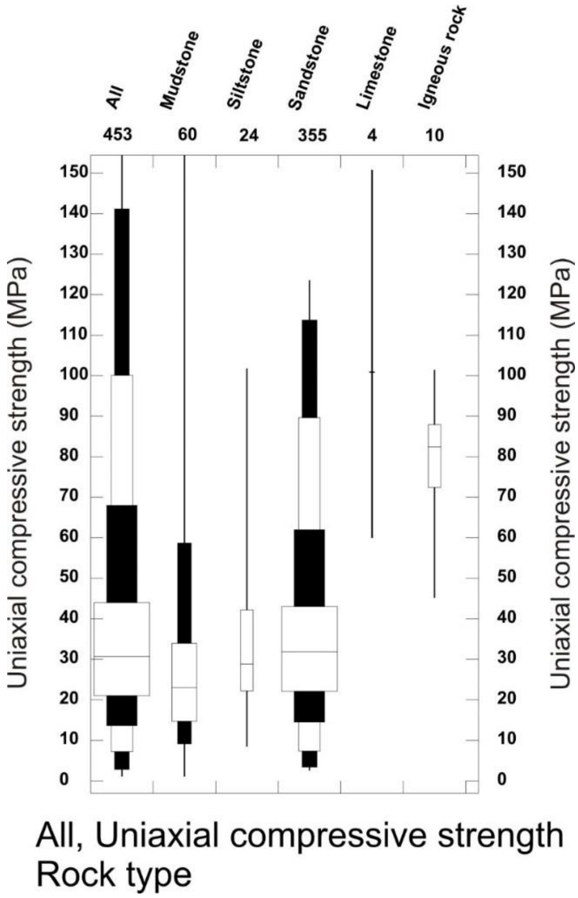


10.3 BEDROCK

10.3.1 Bedrock summary graph

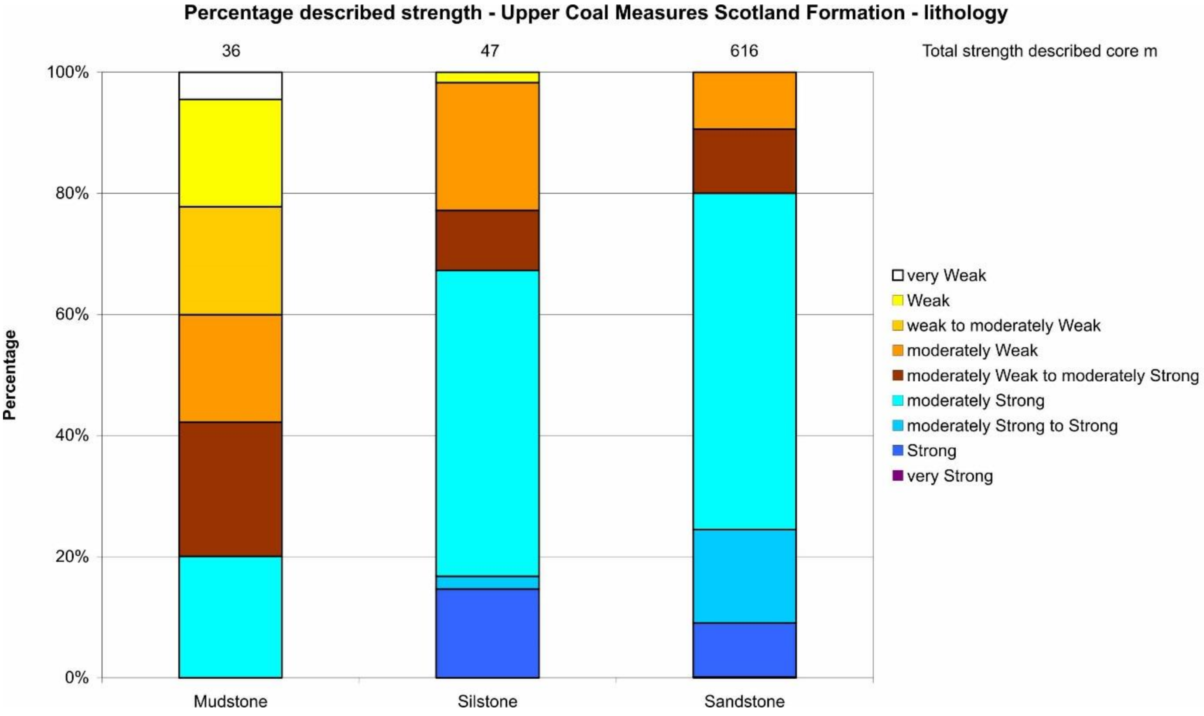
The bar charts below use the old strength classification descriptors as in the original data

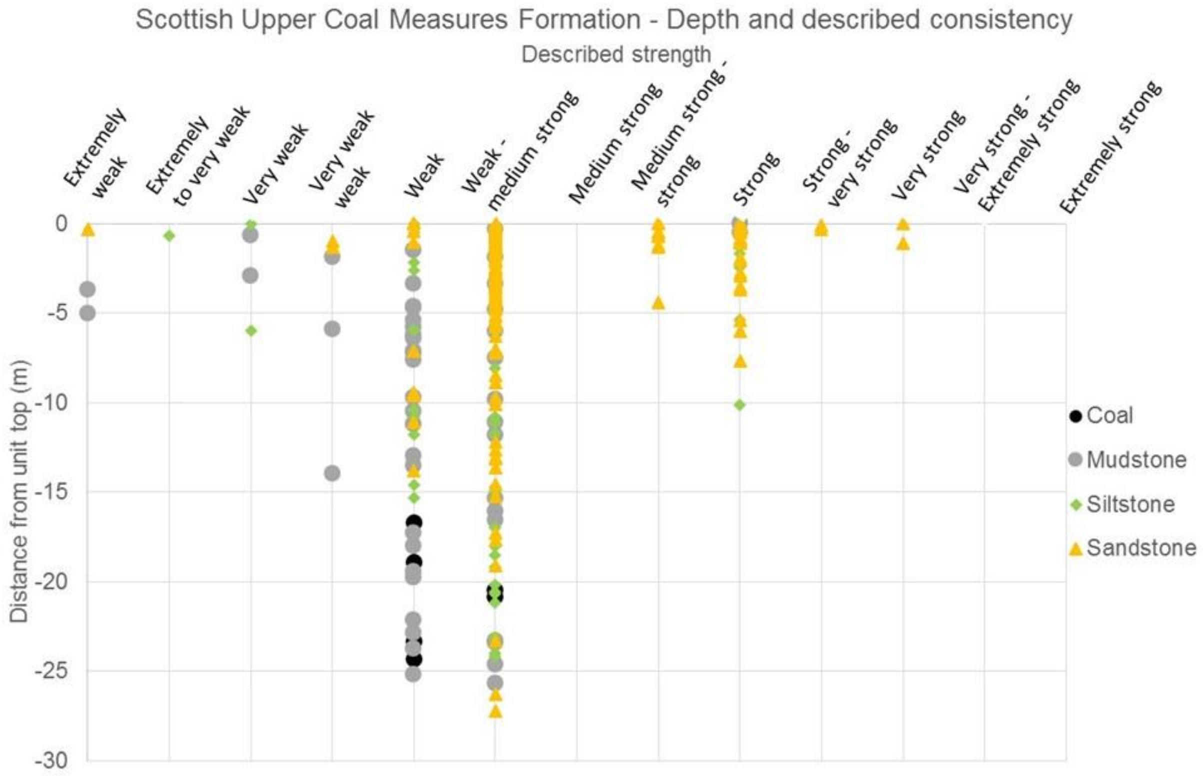


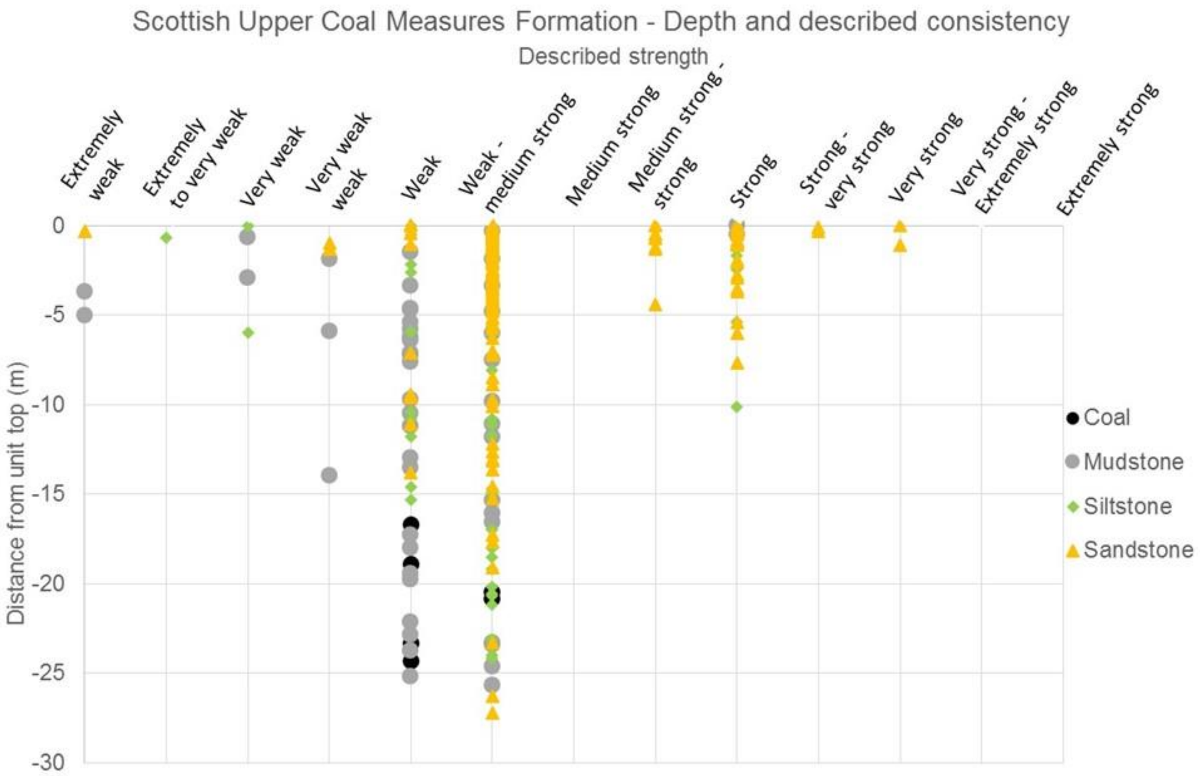

All
Mudstone
Siltstone
Sandstone
Limestone
Igneous rock
453
60
24
355
4
10
Uniaxial compressive strength (MPa)
Uniaxial compressive strength (MPa)
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
All, Uniaxial compressive strength
Rock type

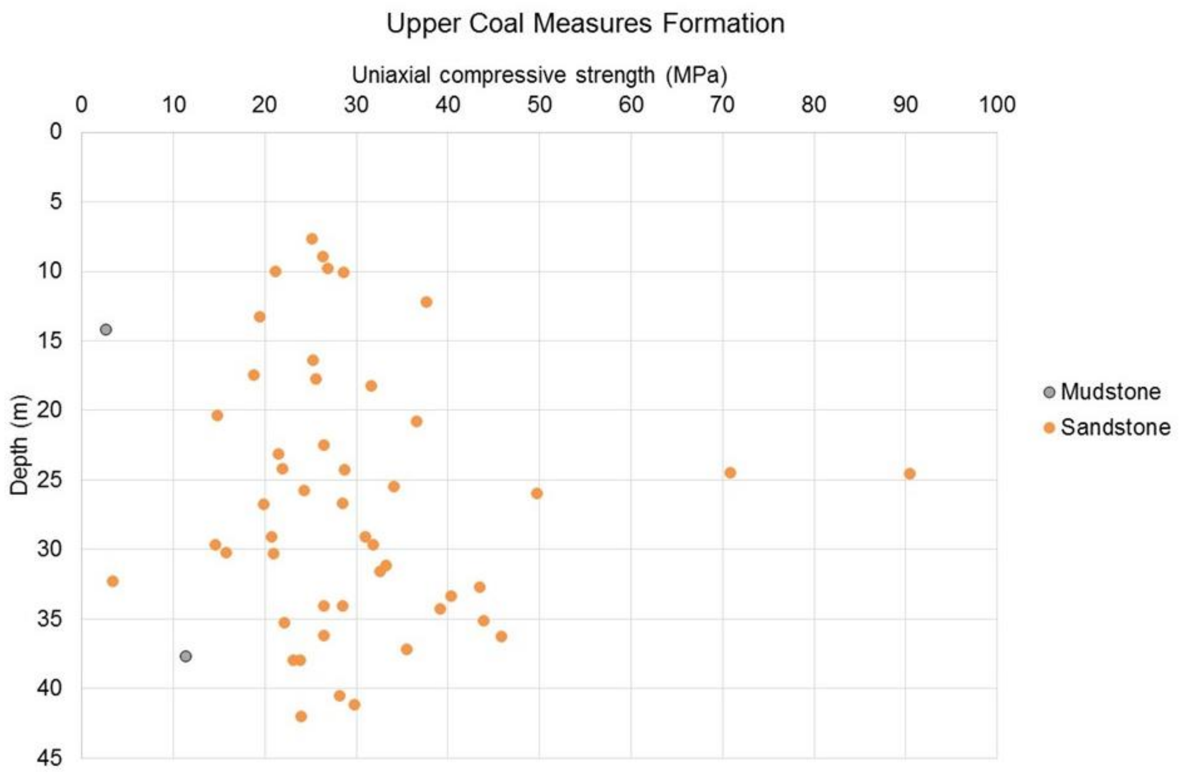
Bedrock units

Scottish Upper Coal Measures Formation

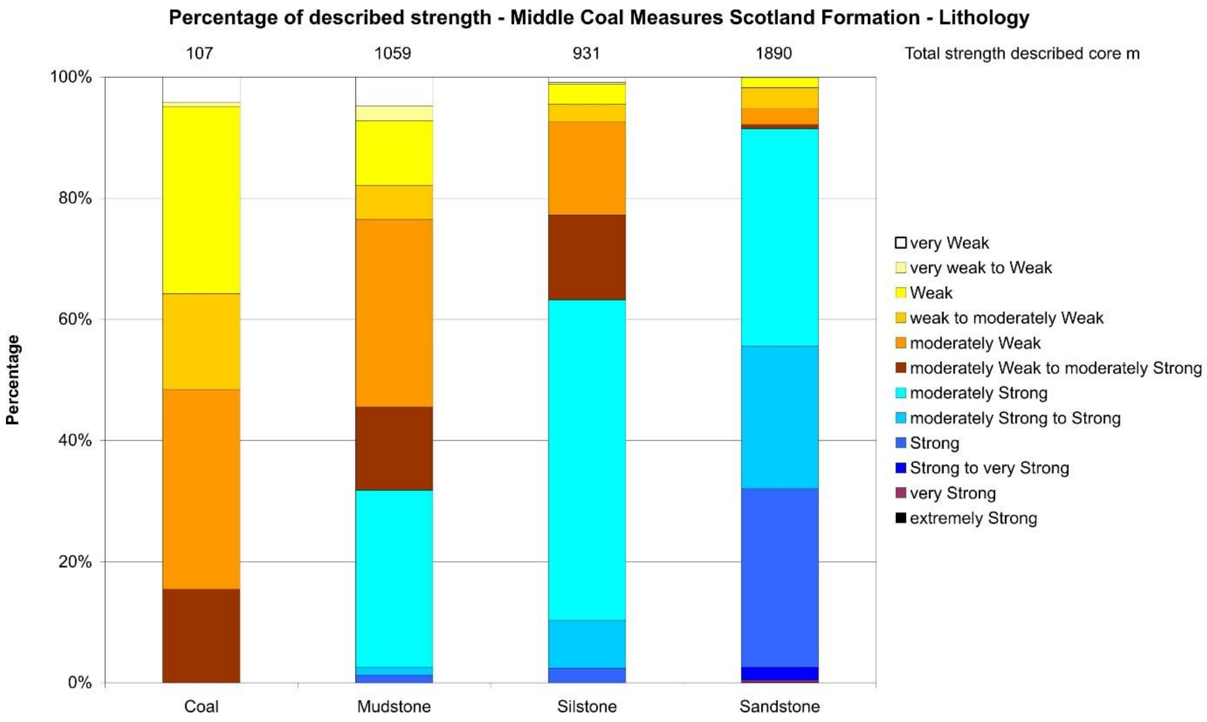




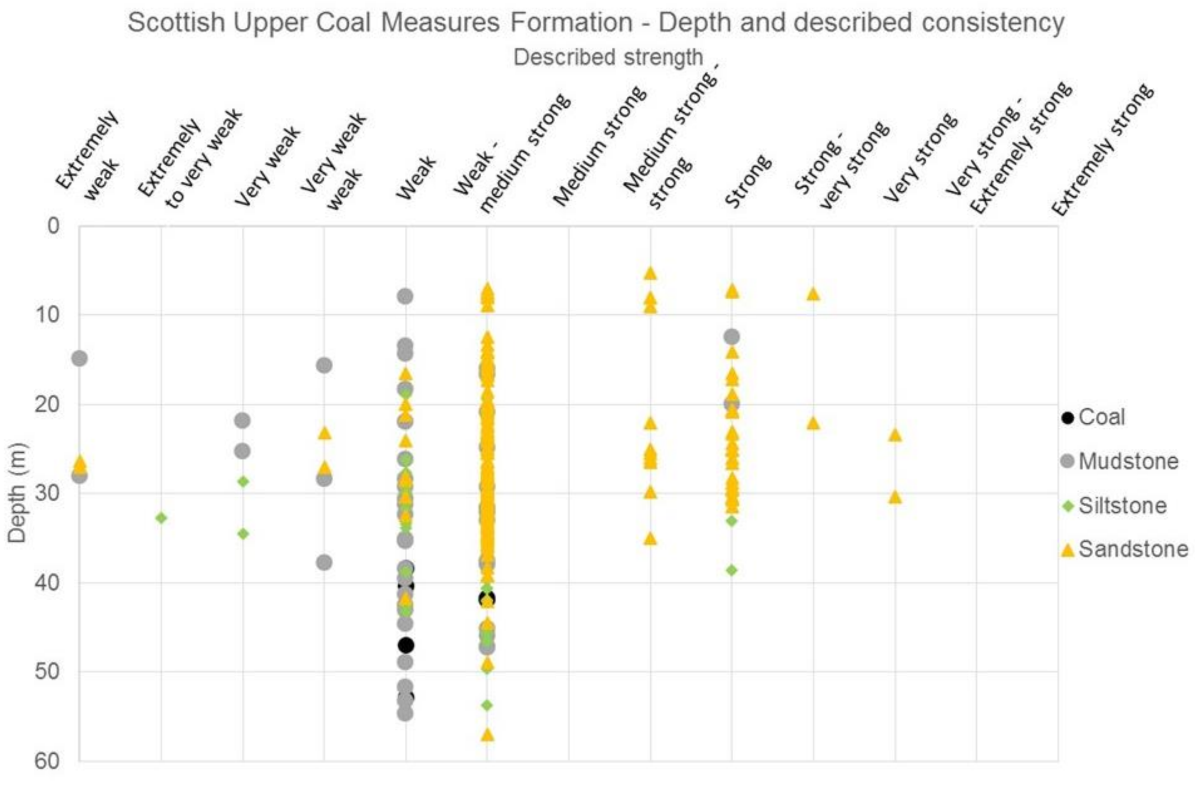




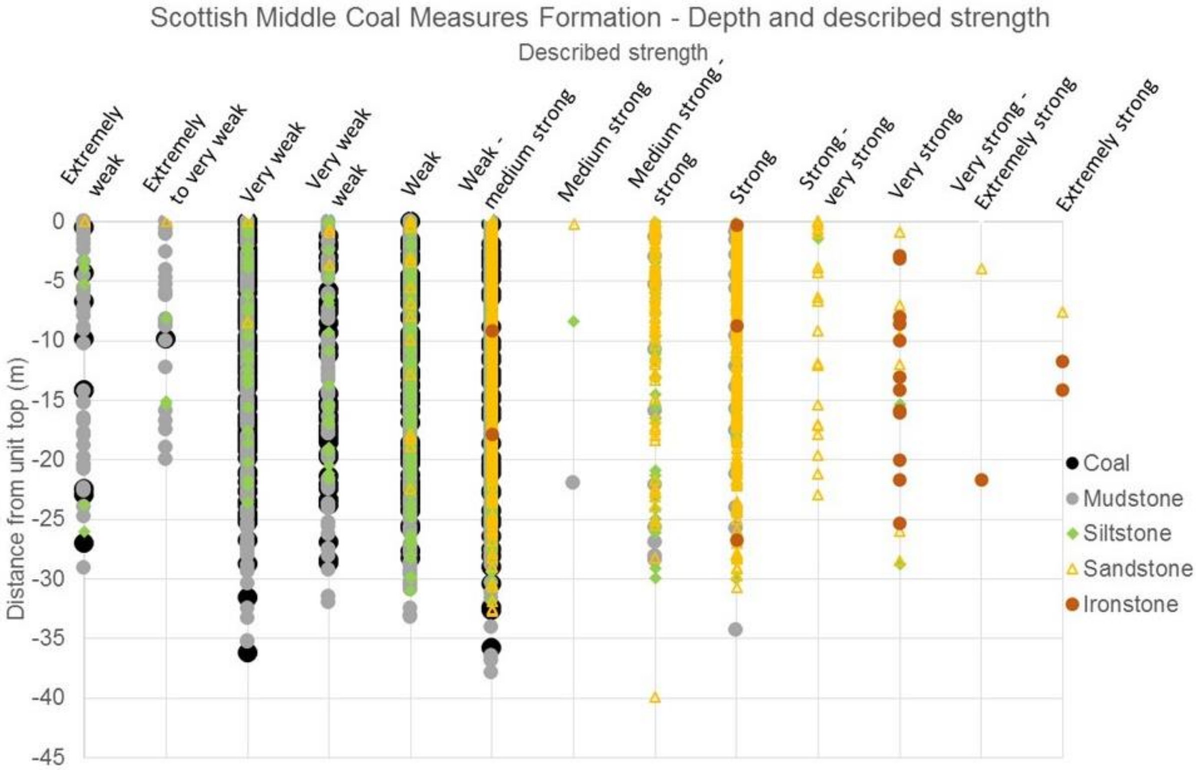
Scottish Middle Coal Measures Formation

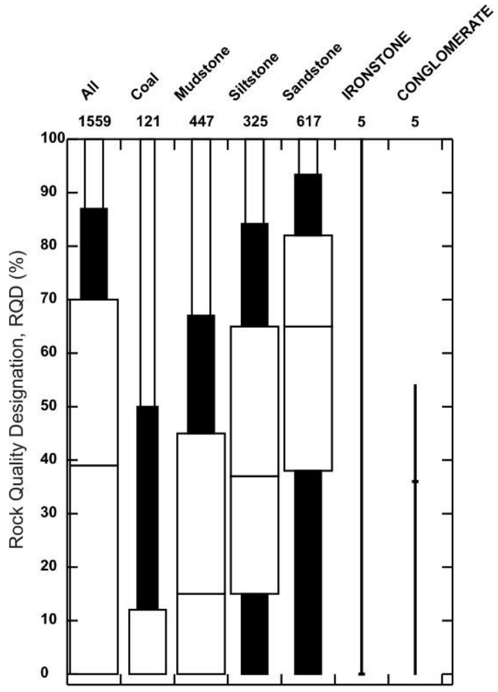


Percentage of described strength - Middle Coal Measures Scotland Formation - Lithology
107
1059
931
1890
Total strength described core m
100%
80%
60%
40%
20%
0%
Percentage
very Weak
very weak to Weak
Weak
weak to moderately Weak
moderately Weak
moderately Weak to moderately Strong
moderately Strong
moderately Strong to Strong
Strong
Strong to very Strong
very Strong
extremely Strong
Coal
Mudstone
Silstone
Sandstone

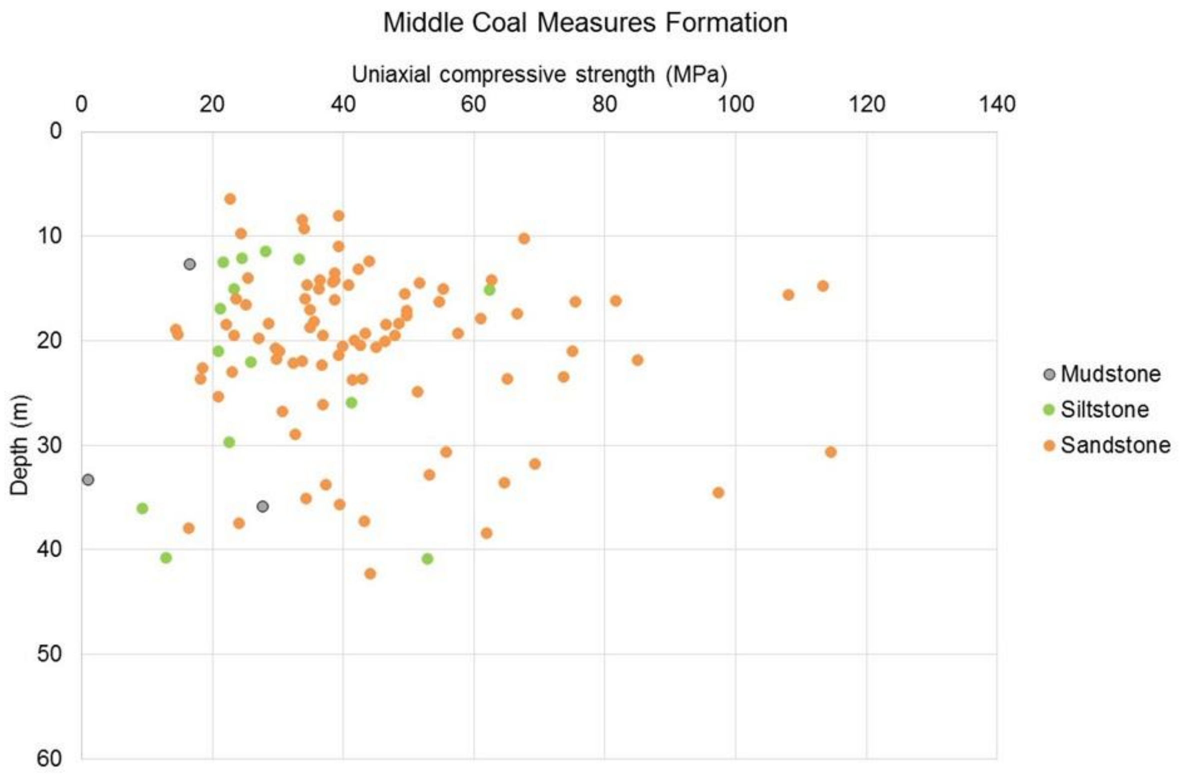


Scottish Upper Coal Measures Formation - Depth and described consistency
Described strength
Extremely weak
Extremely to very weak
Very weak
Very weak weak
Weak
Weak - medium strong
Medium strong
Medium strong - strong
Strong
Strong - very strong
Very strong
Very strong - Extremely strong
Extremely strong
Depth (m)
0
10
20
30
40
50
60
Coal
Mudstone
Siltstone
Sandstone

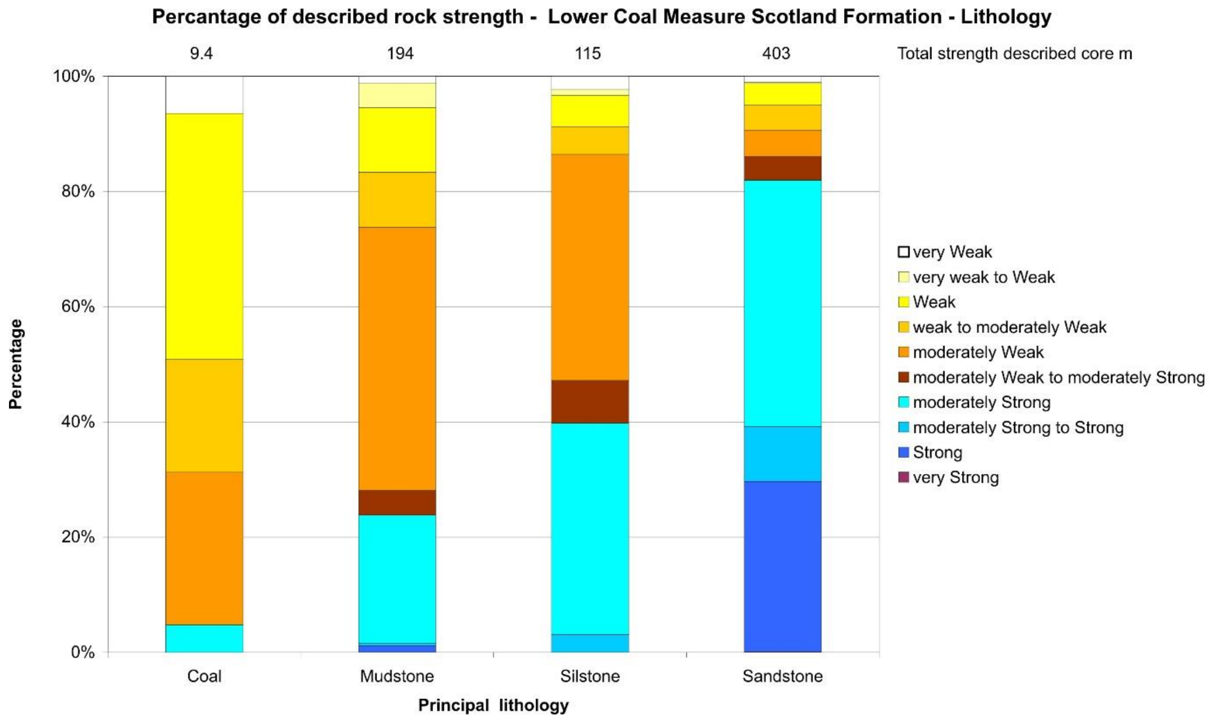


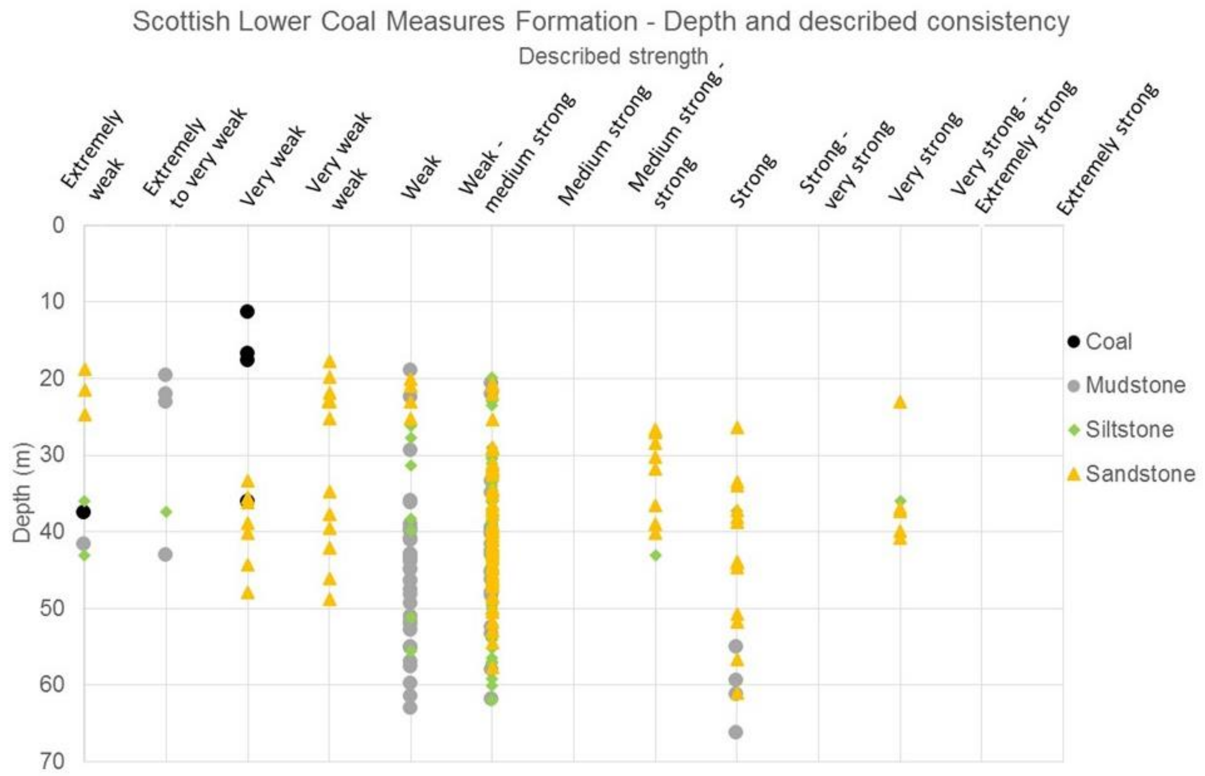


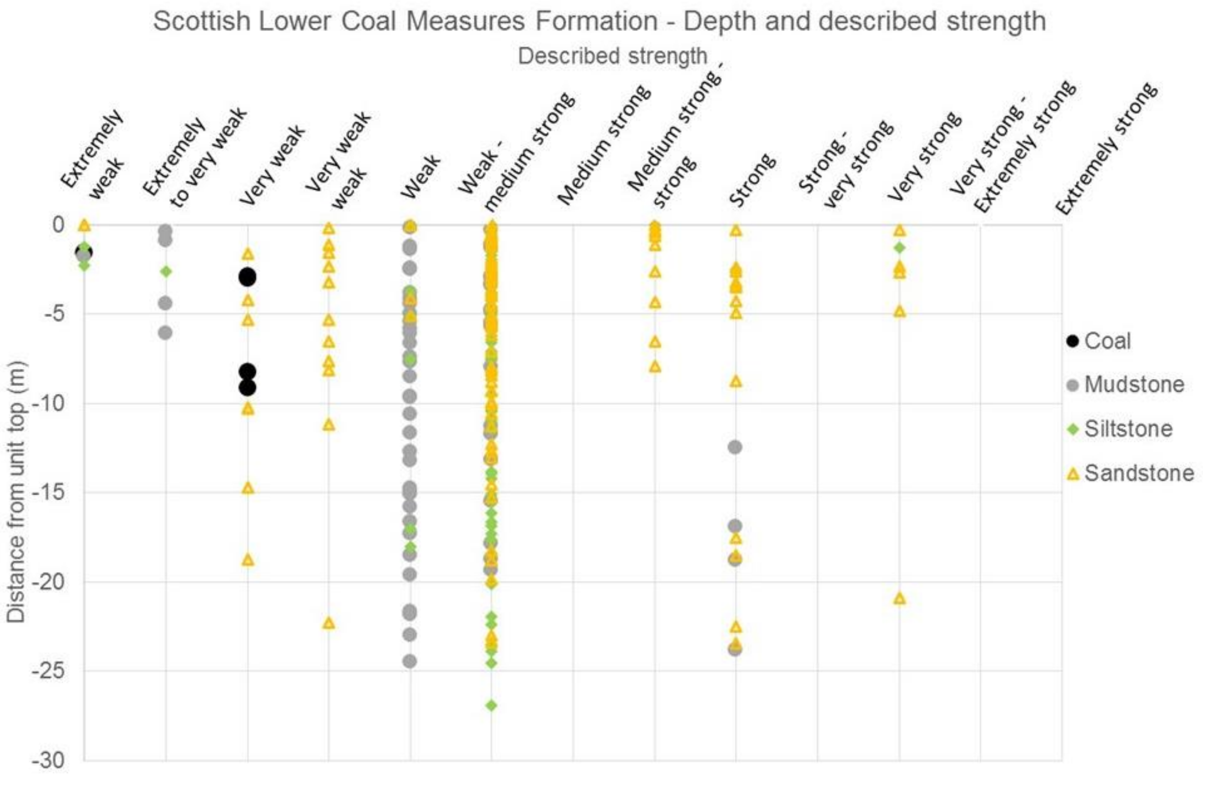
Extended Whisker plot of
Middle Coal Measures Scotland
Rock Quality Designation (RQD) by lithology

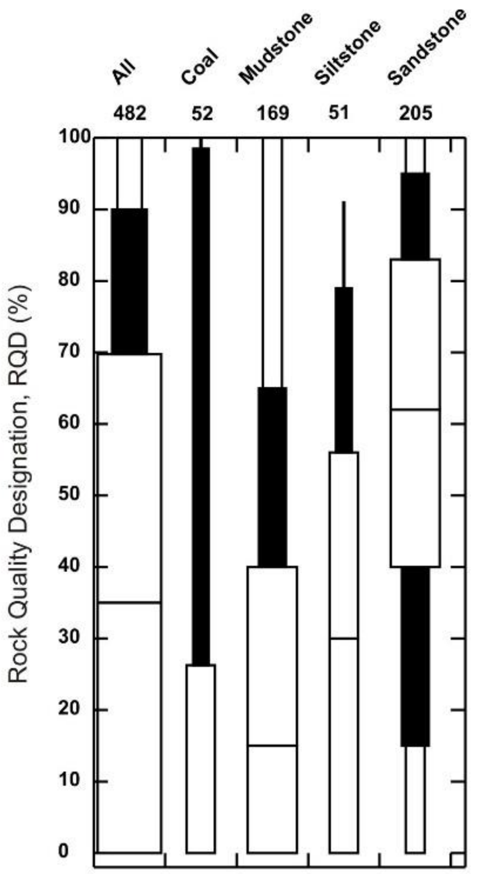


Scottish Lower Coal Measures Formation

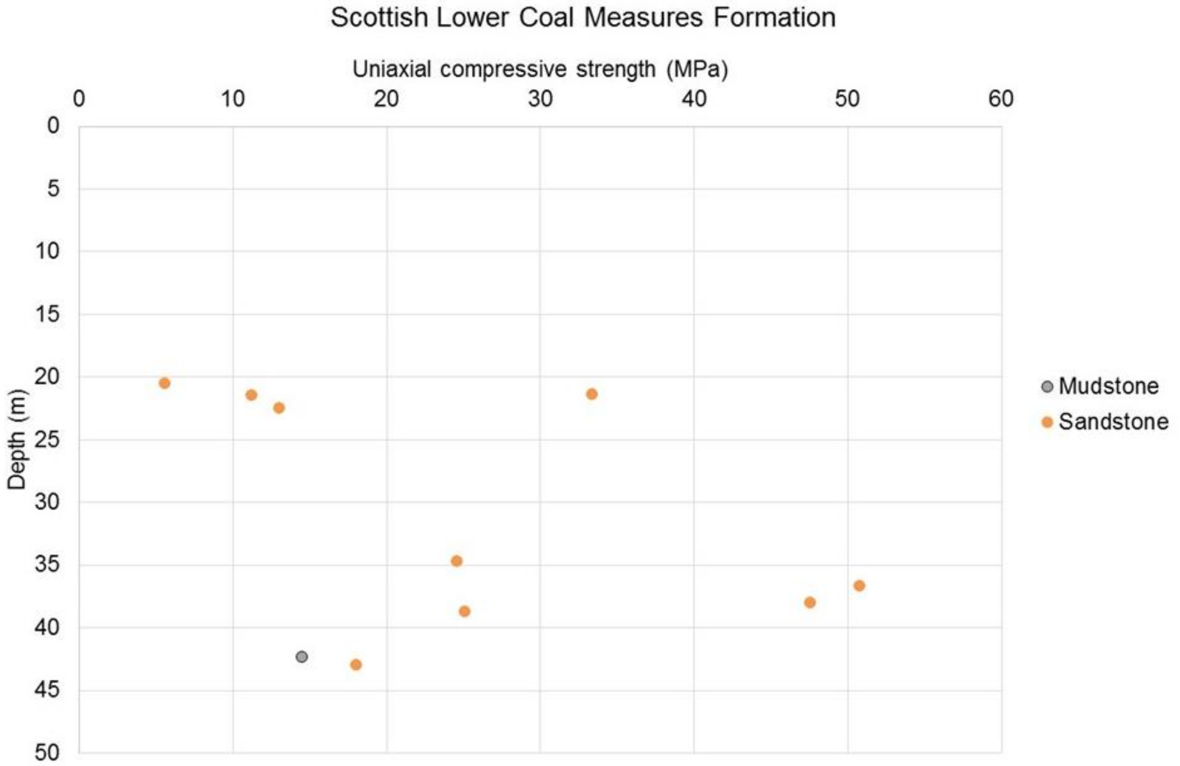



Scottish Lower Coal Measures Formation - Depth and described consistency
Described strength
Extremely weak
Extremely to very weak
Very weak
Very weak weak
Weak
Weak - medium strong
Medium strong
Medium strong - strong
Strong
Strong - very strong
Very strong
Very strong - Extremely strong
Extremely strong
Depth (m)
0
10
20
30
40
50
60
70
Coal
Mudstone
Siltstone
Sandstone

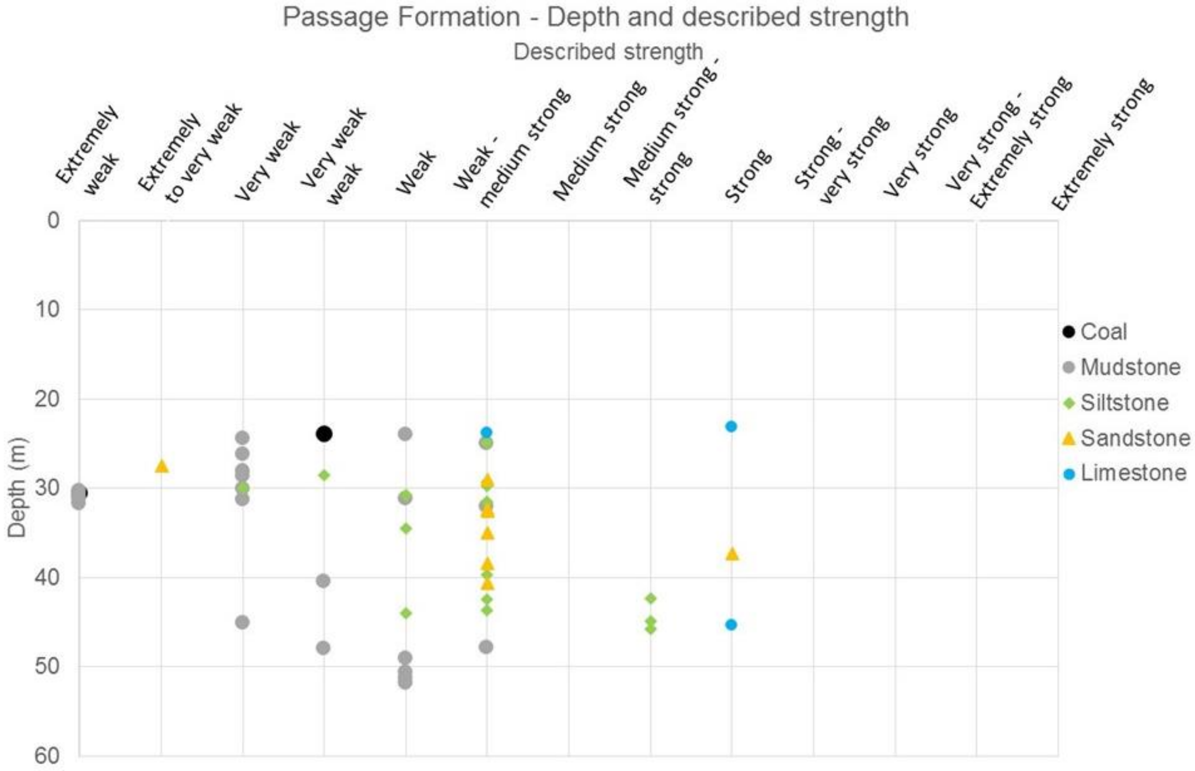

Scottish Lower Coal Measures Formation - Depth and described strength
Described strength
Extremely weak
Extremely to very weak
Very weak
Very weak weak
Weak
Weak - medium strong
Medium strong
Medium strong - strong
Strong
Strong - very strong
Very strong
Very strong - Extremely strong
Extremely strong
Distance from unit top (m)
0
-5
-10
-15
-20
-25
-30
Coal
Mudstone
Siltstone
Sandstone

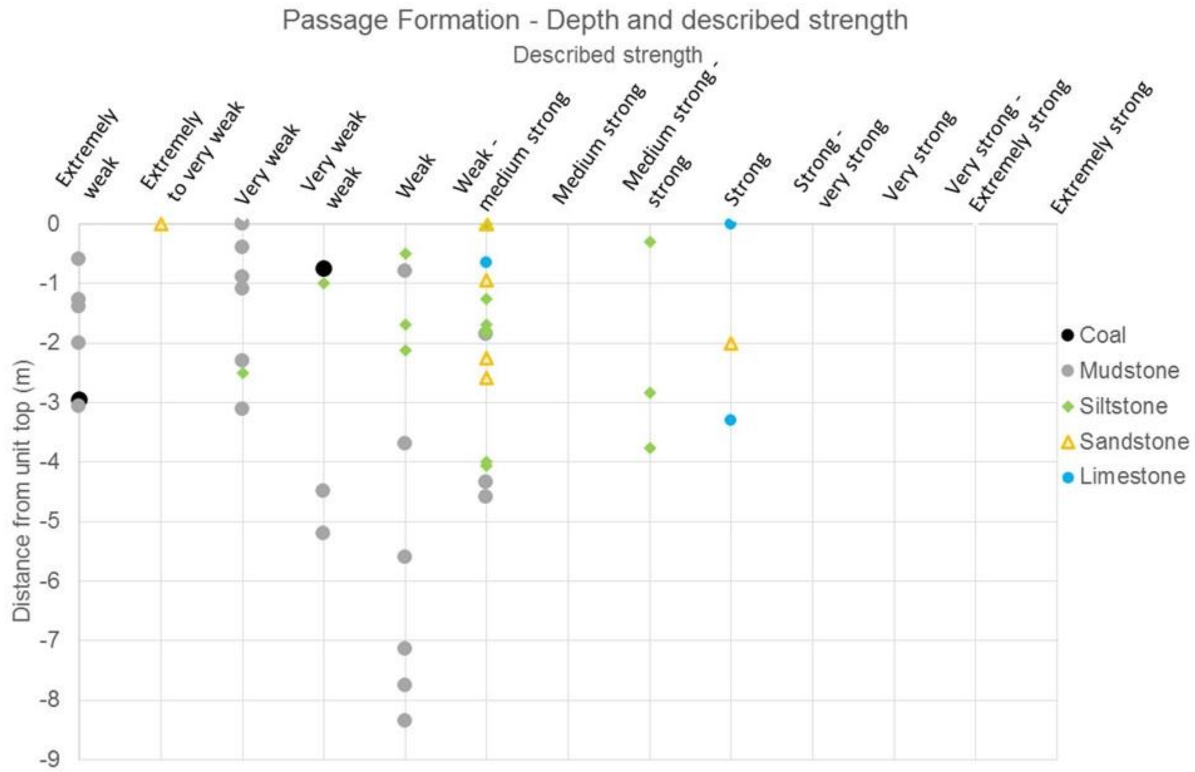


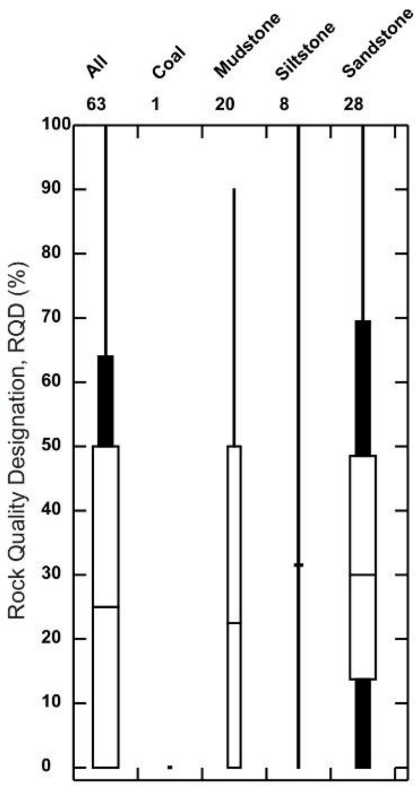
Extended Whisker plot for Lower Coal Measures Scotland
Rock Quality Designation (RQD) by lithology



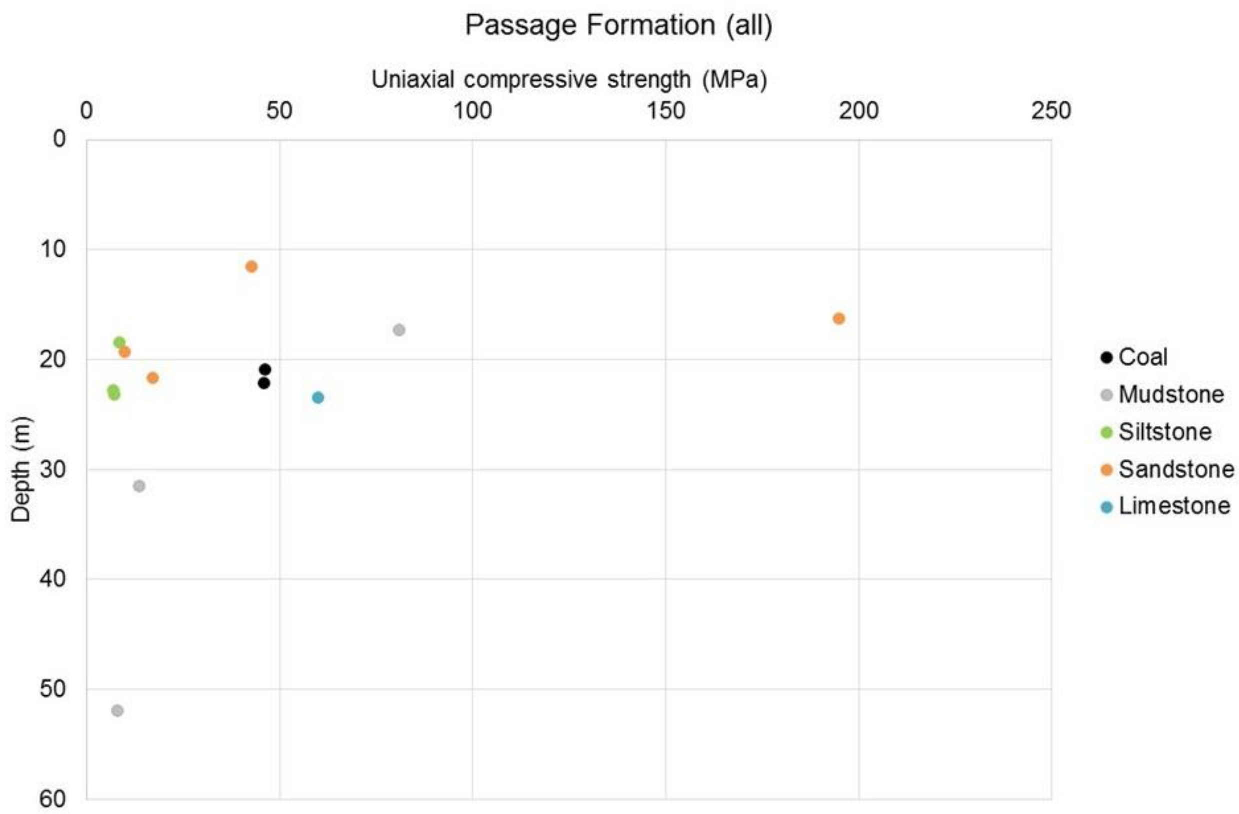
Passage Formation

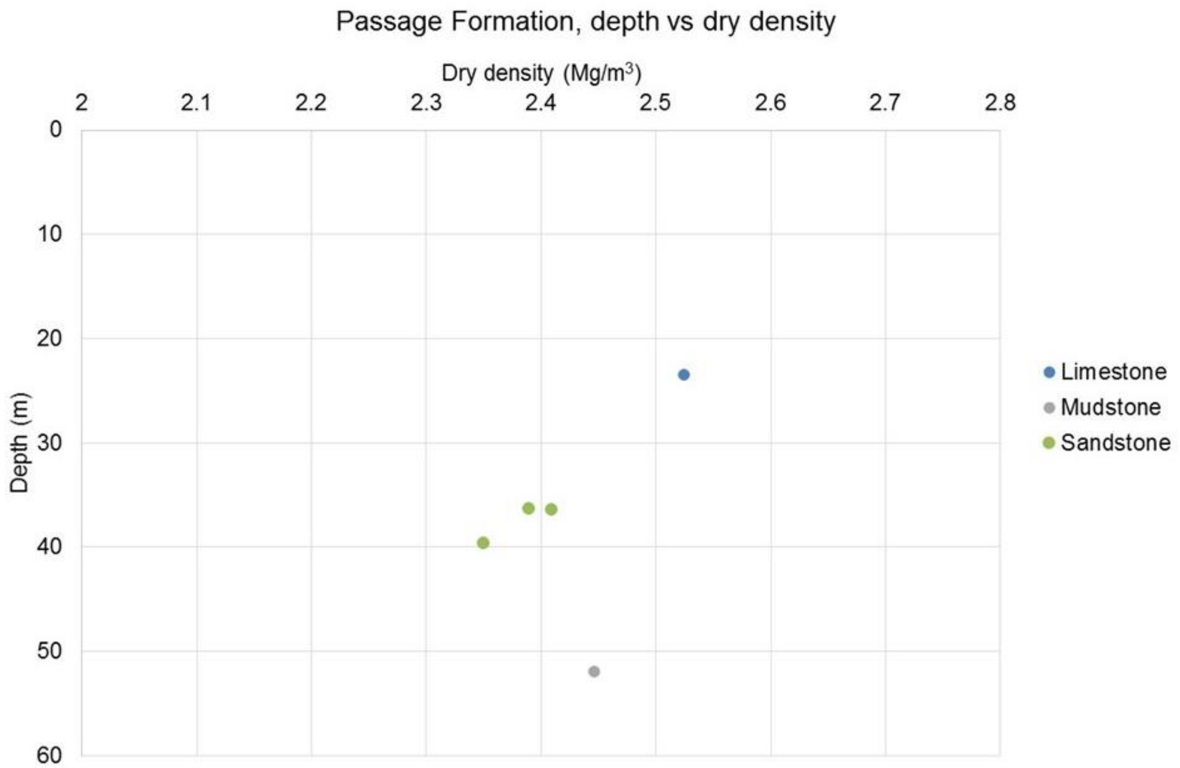

Passage Formation - Depth and described strength
Described strength
Extremely weak
Extremely to very weak
Very weak
Very weak weak
Weak
Weak - medium strong
Medium strong
Medium strong - strong
Strong
Strong - very strong
Very strong
Very strong - Extremely strong
Extremely strong
Depth (m)
0
10
20
30
40
50
60
Coal
Mudstone
Siltstone
Sandstone
Limestone


Passage Formation - Depth and described strength
Described strength
Extremely weak
Extremely to very weak
Very weak
Very weak weak
Weak
Weak - medium strong
Medium strong
Medium strong - strong
Strong
Strong - very strong
Very strong
Very strong - Extremely strong
Extremely strong
Distance from unit top (m)
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
Coal
Mudstone
Siltstone
Sandstone
Limestone

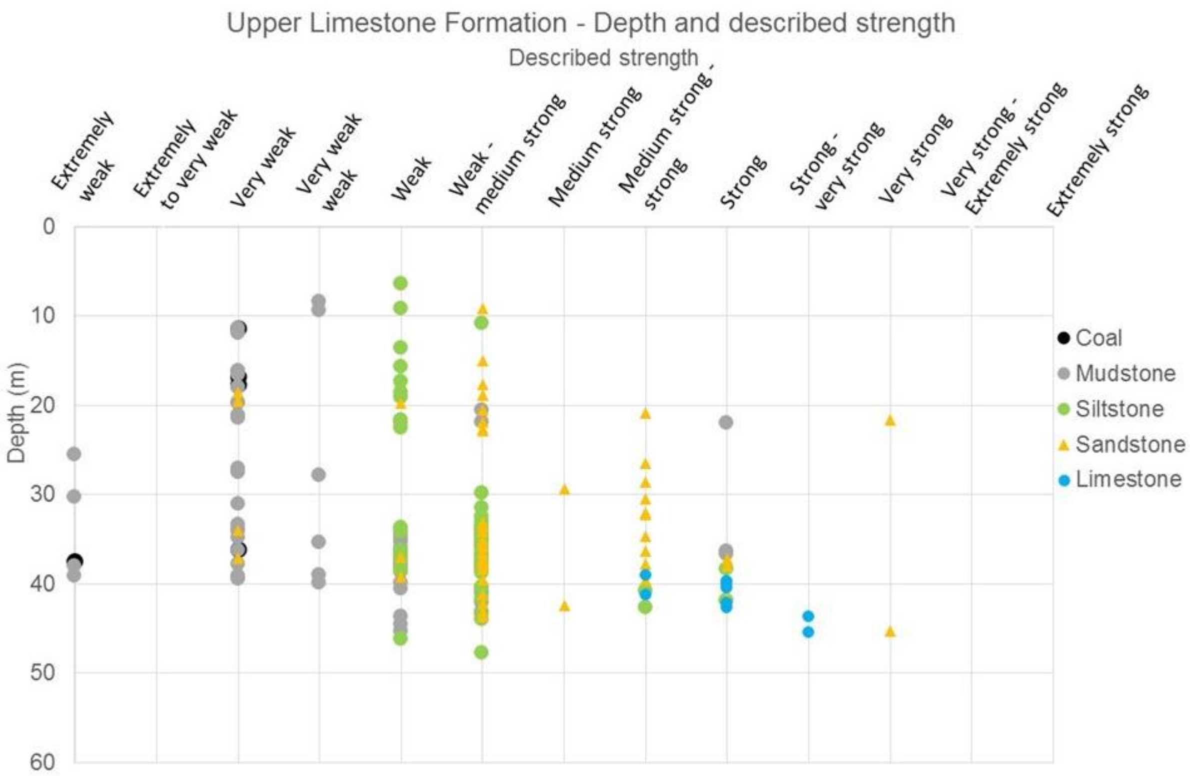


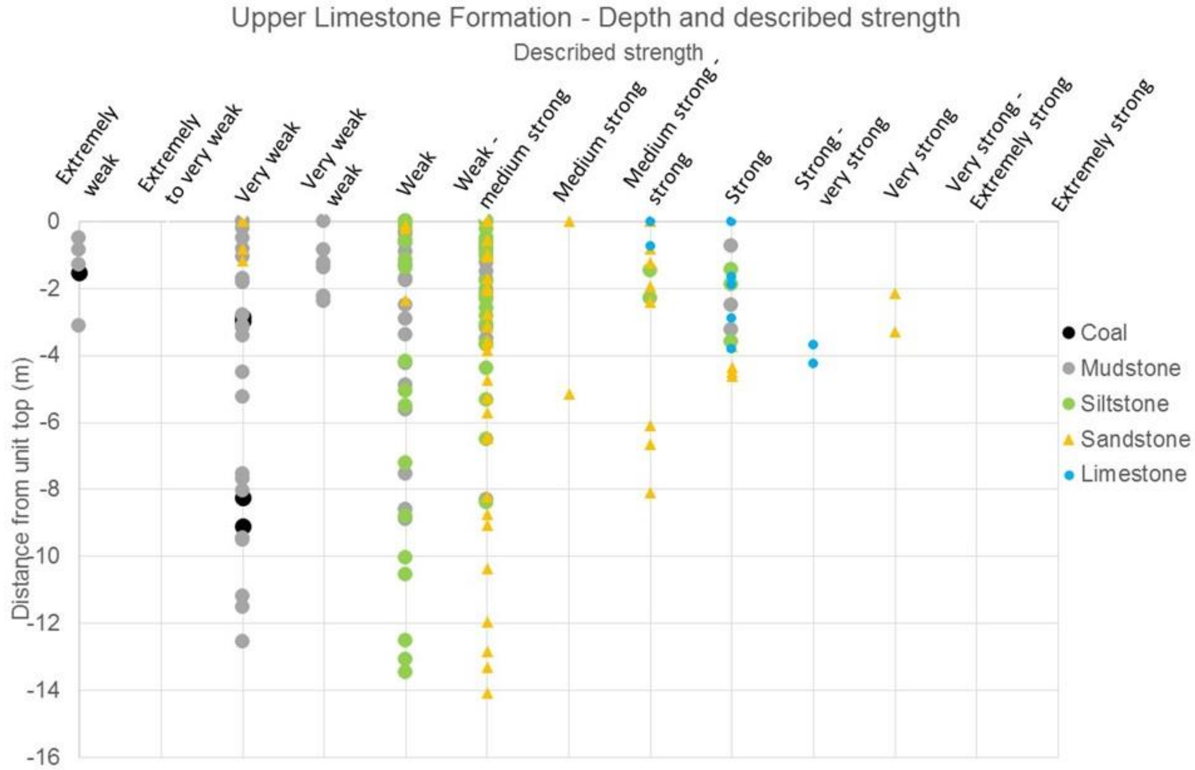
Extended Whisker plot for
Passage Formation
Rock Quality Designation (RQD) by lithology

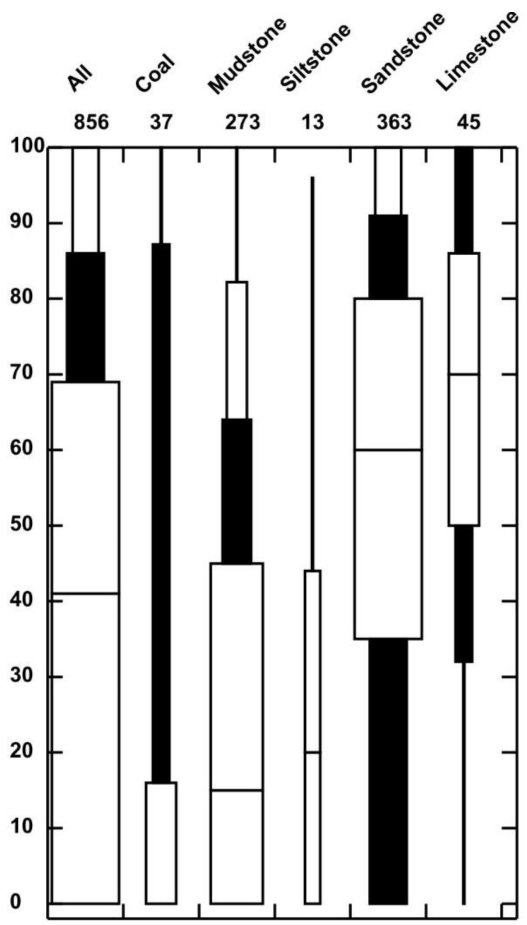




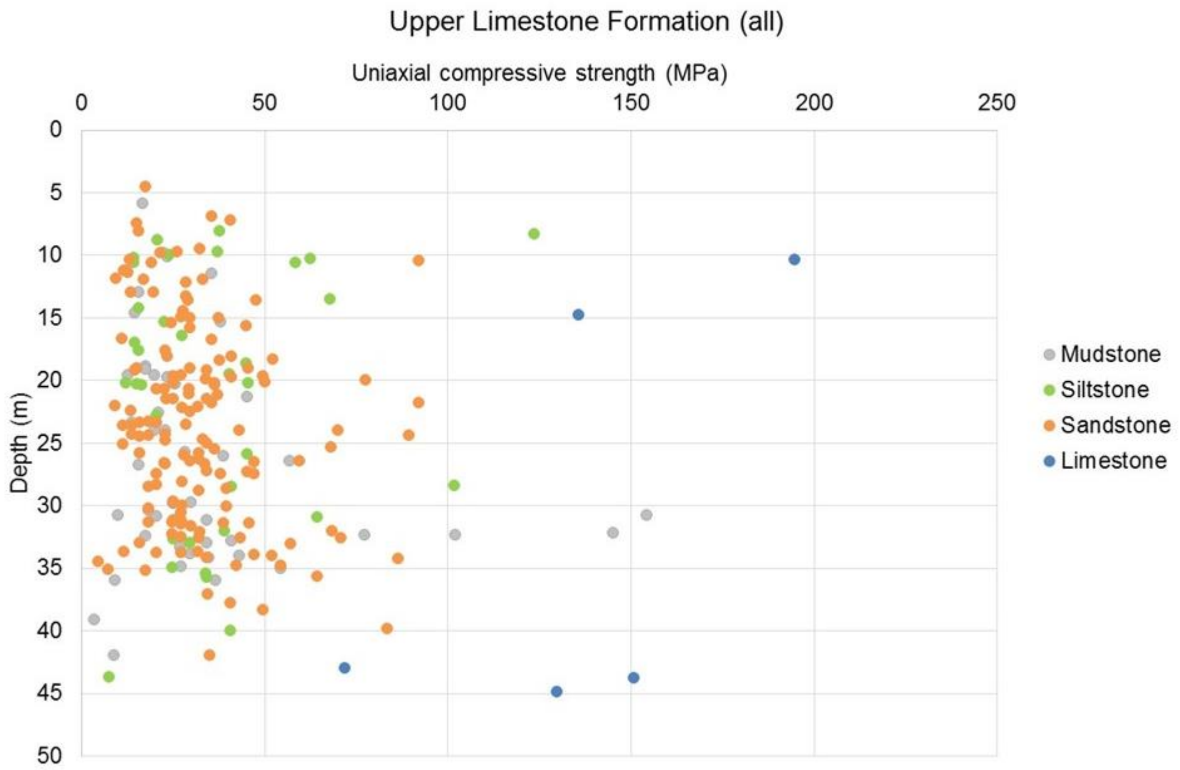
Upper Limestone Formation

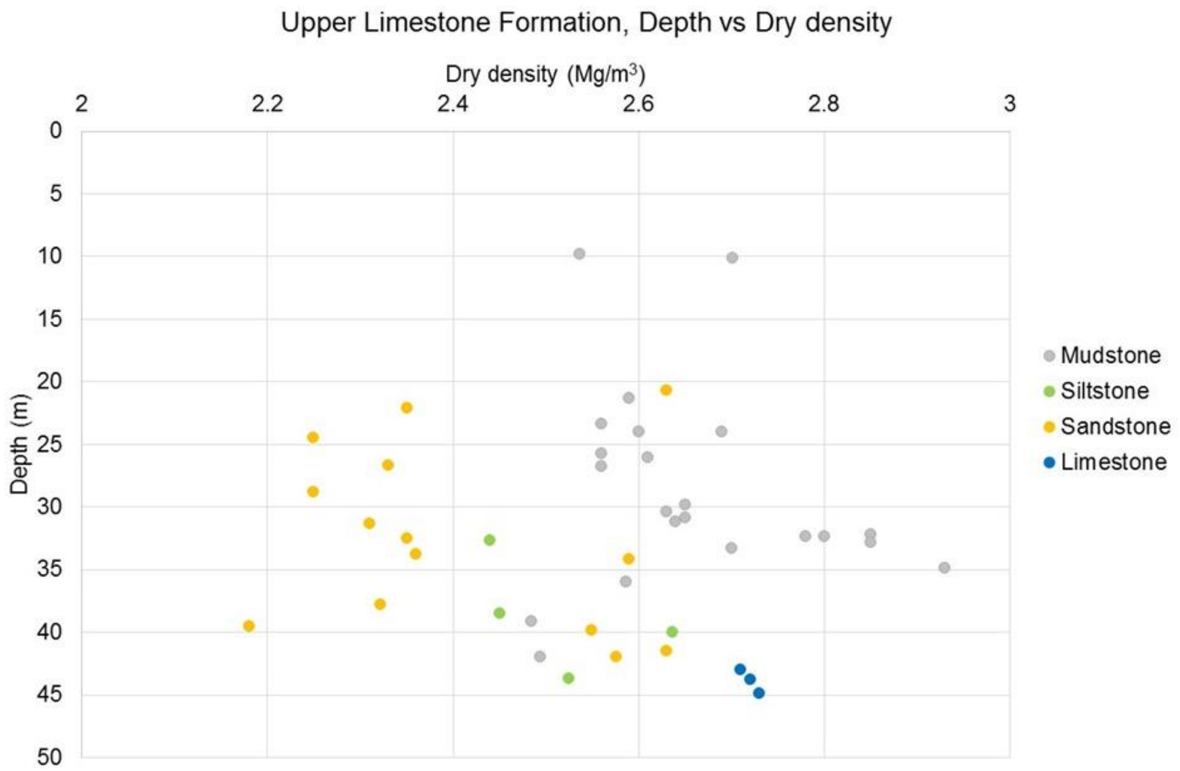




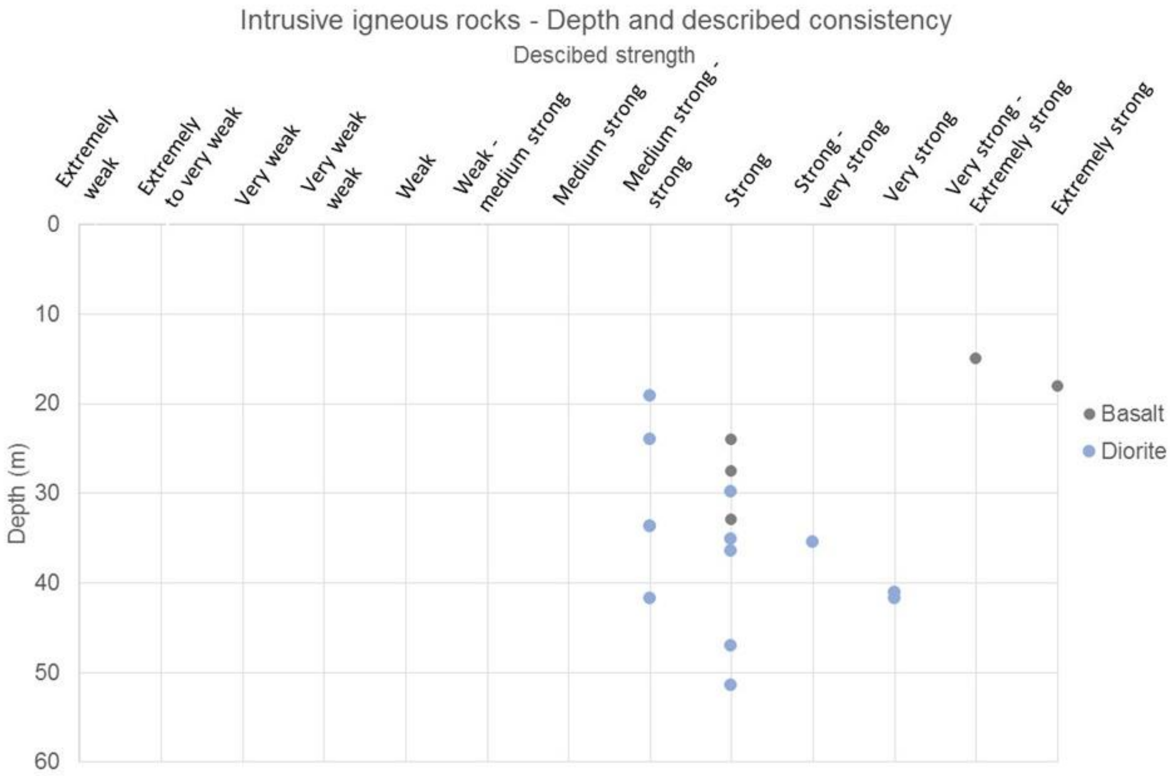


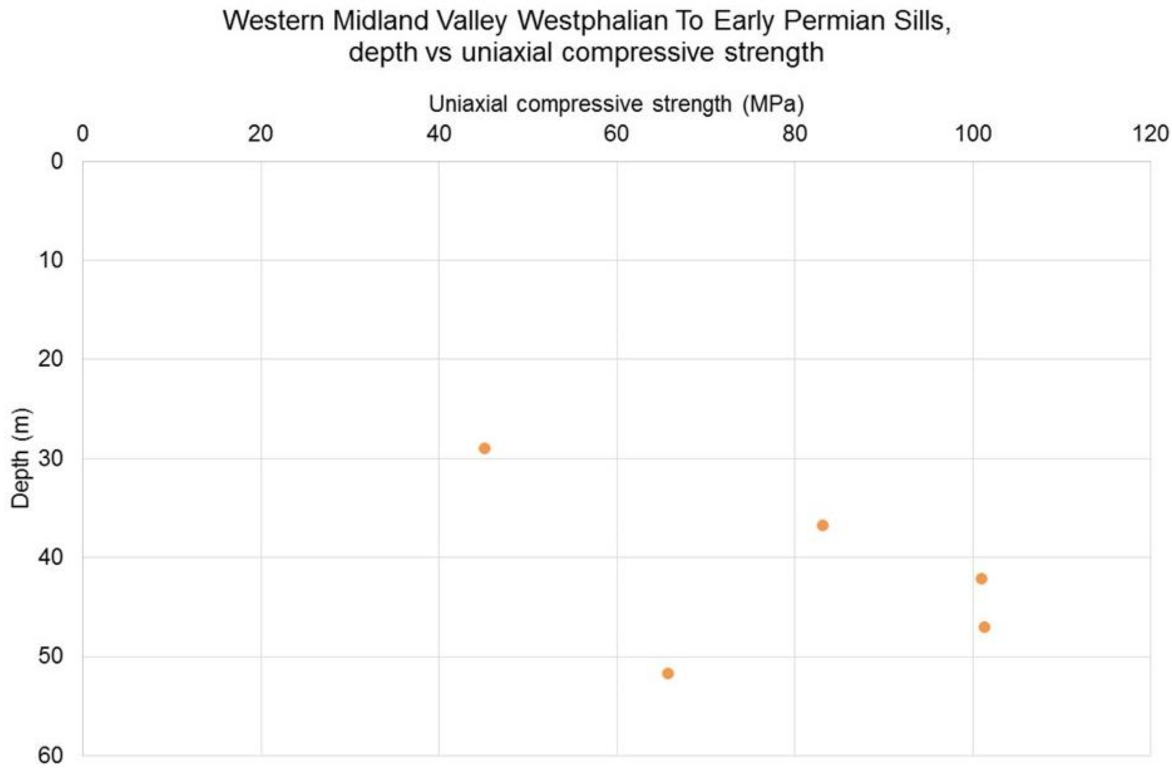
Extended Whisker plot for
Upper Limestone Formation
Rock Quality Designation (RQD) by lithology


Upper Limestone Formation (all)
Uniaxial compressive strength (MPa)
0
50
100
150
200
250
0
5
10
15
20
25
30
35
40
45
50
Depth (m)
Mudstone
Siltstone
Sandstone
Limestone


Upper Limestone Formation, Depth vs Dry density
Dry density (Mg/m3)
2
2.2
2.4
2.6
2.8
3
0
5
10
15
20
25
30
35
40
45
50
Depth (m)
Mudstone
Siltstone
Sandstone
Limestone

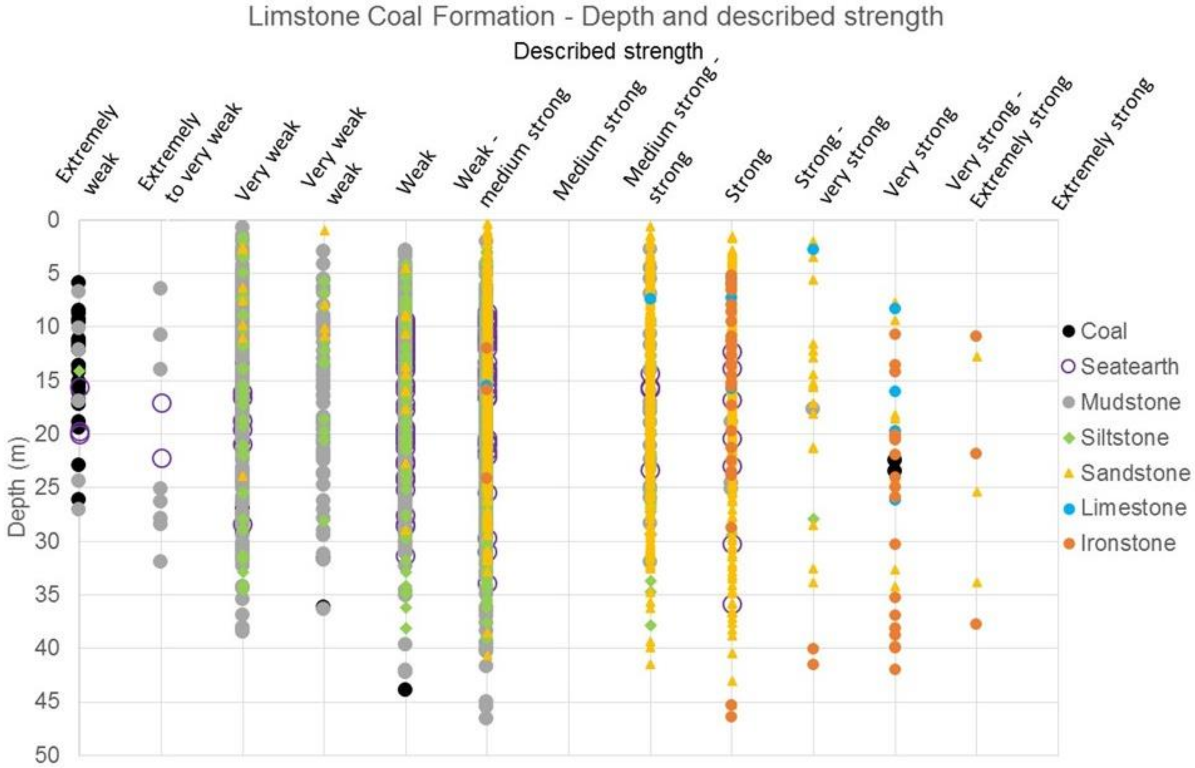
Intrusive igneous rocks (Western Midland Valley Westphalian to Early Permian Sills, WMVAS)

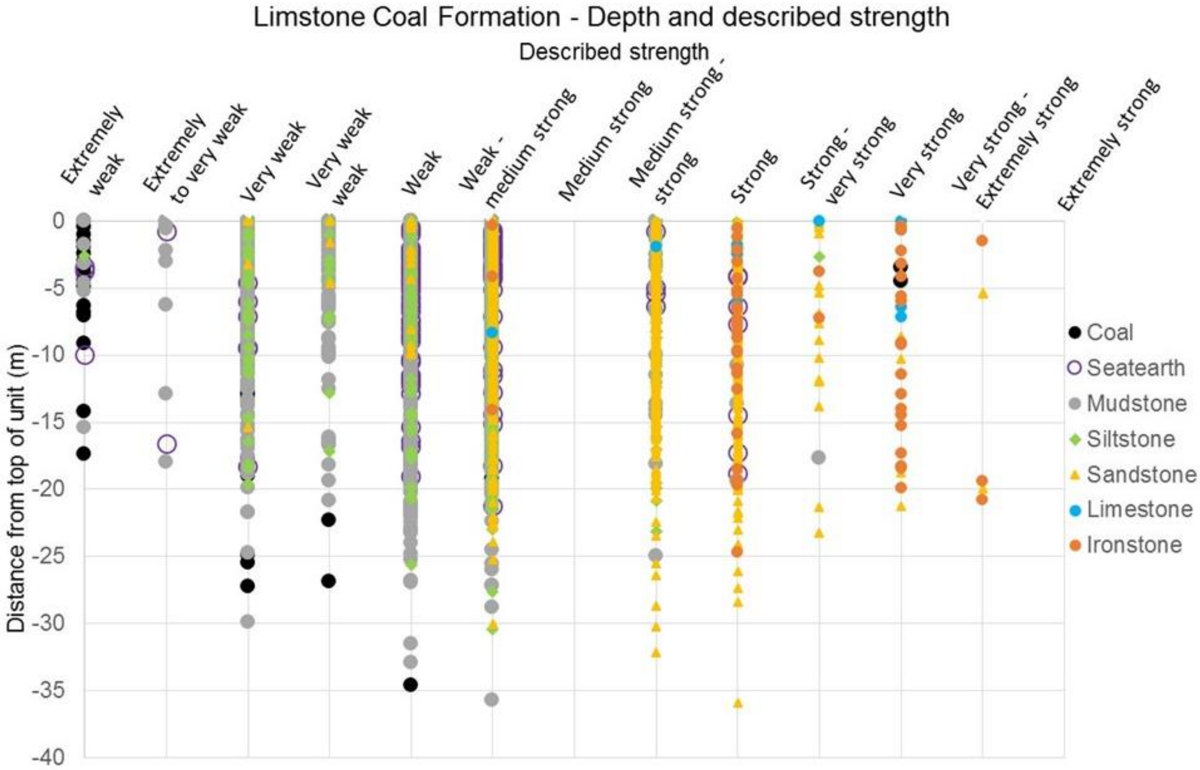


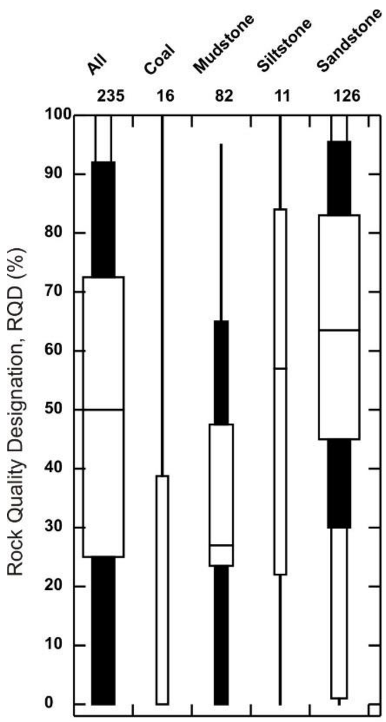


Limestone Coal Formation

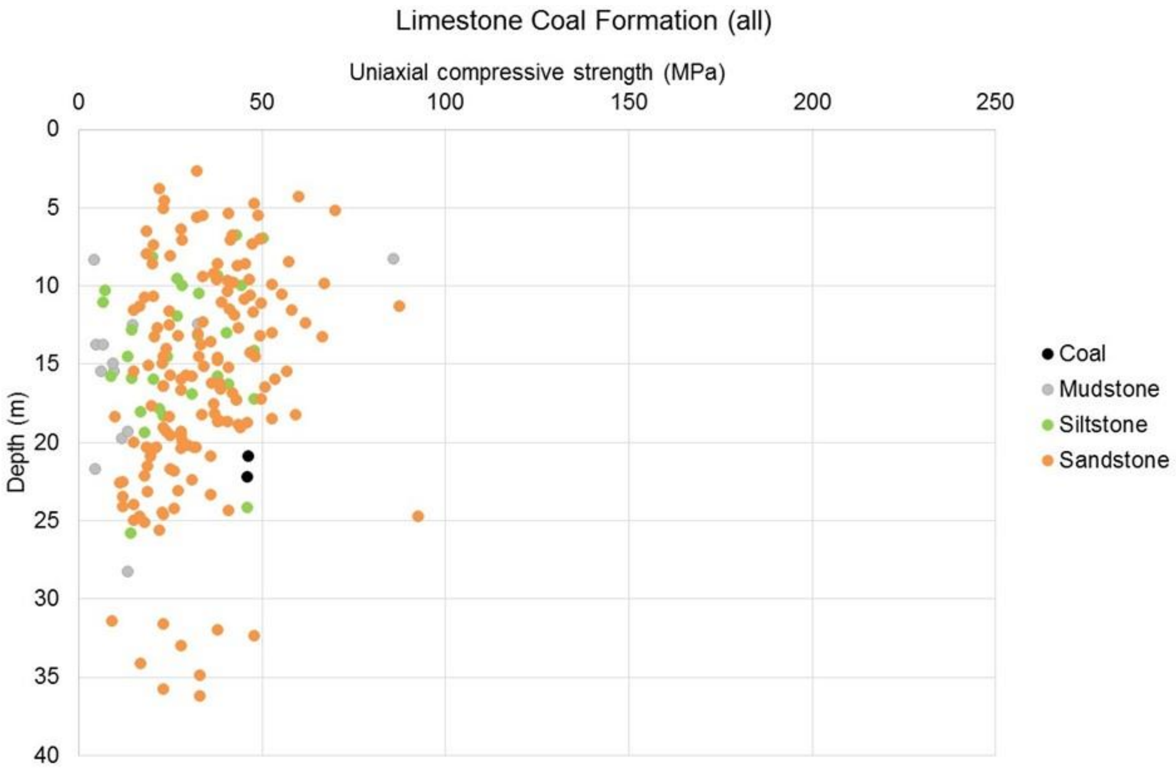
Limestone Coal Formation



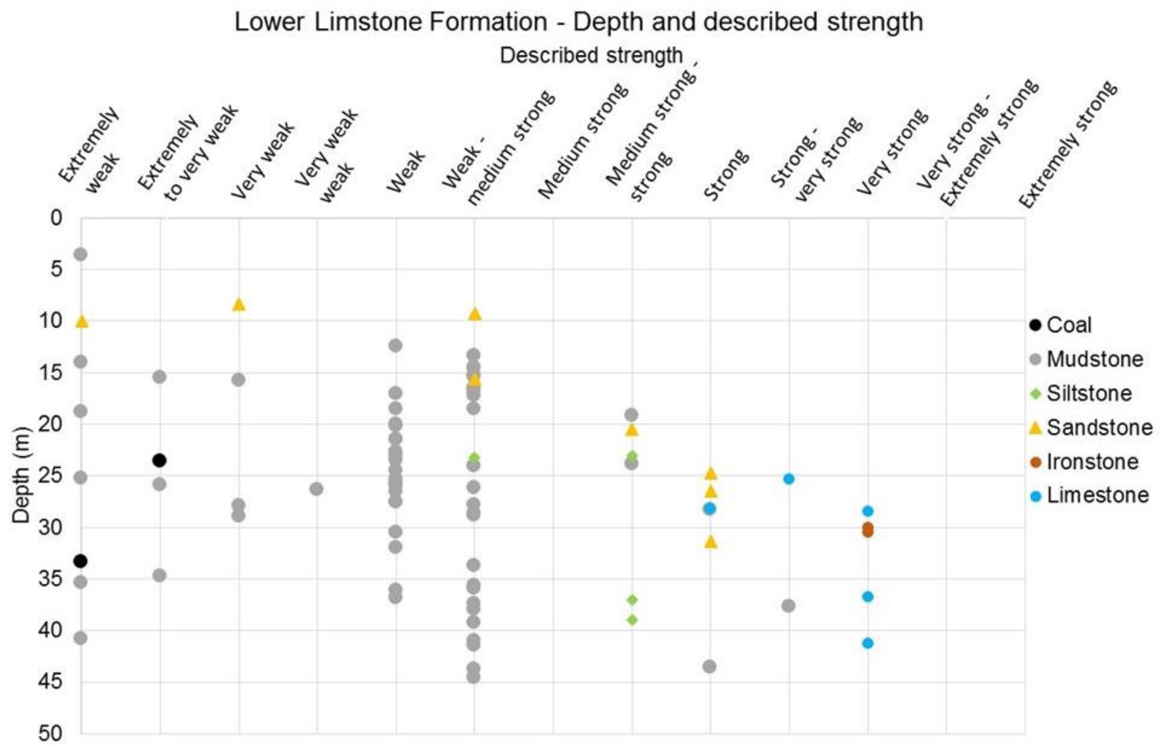


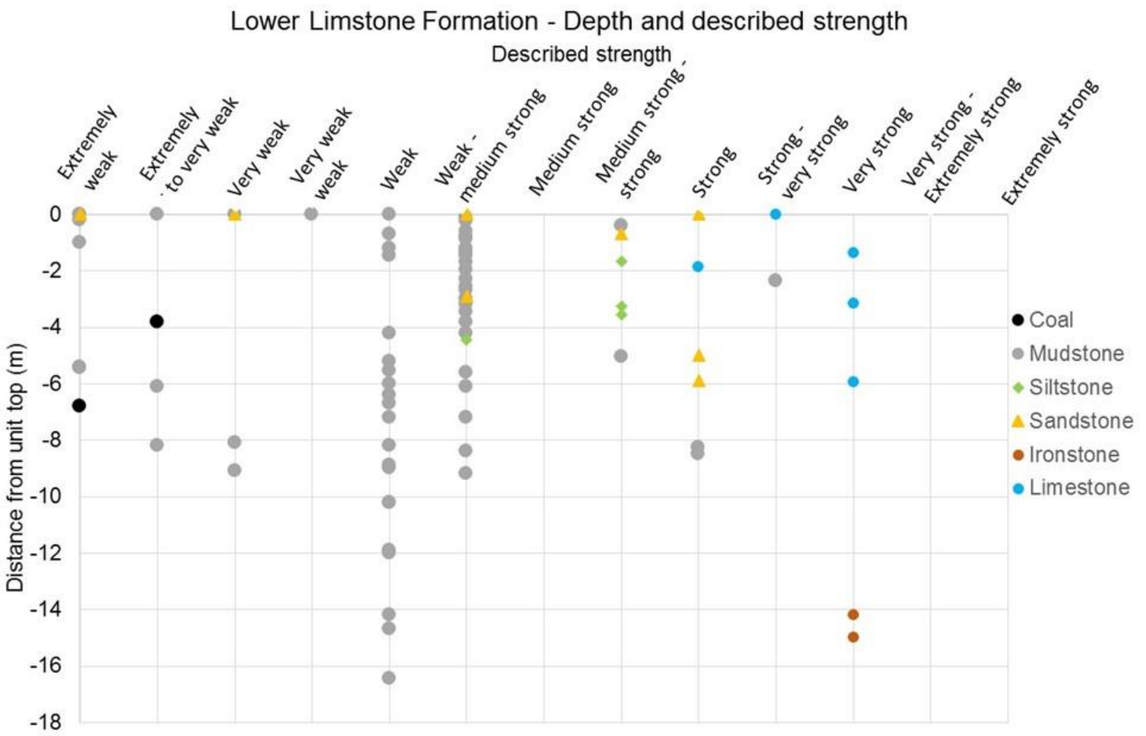


Extended Whisker plot for
Lower Limestone Coal Formation
Rock Quality Designation (RQD) by lithology



Lower Limestone Formation


Lower Limstone Formation - Depth and described strength
Described strength
Extremely weak
Extremely to very weak
Very weak
Very weak weak
Weak
Weak - medium strong
Medium strong
Medium strong - strong
Strong
Strong - very strong
Very strong
Very strong - Extremely strong
Extremely strong
Depth (m)
0
5
10
15
20
25
30
35
40
45
50
Coal
Mudstone
Siltstone
Sandstone
Ironstone
Limestone


Lower Limstone Formation - Depth and described strength
Described strength
Extremely weak
Extremely to very weak
Very weak
Very weak weak
Weak
Weak - medium strong
Medium strong
Medium strong - strong
Strong
Strong - very strong
Very strong
Very strong - Extremely strong
Extremely strong
Distance from unit top (m)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
Coal
Mudstone
Siltstone
Sandstone
Ironstone
Limestone

Appendix 3 UK Geoenergy Observatories: Glasgow Geothermal Energy Research Field Site (GGERFS). Vision

Note: this section was added in May 2017, some time after the report was written.

Geothermal energy has the potential to provide continuous, sustainable, low carbon and renewable heat (and electricity) to many of the homes and workplaces in the UK. However, this potential baseload contribution to the UK's energy mix, and to decarbonisation of its energy, is as yet largely unrealised.

The BGS (NERC) UKGEOS project's Glasgow Geothermal Energy Research Field Site (GGERFS) is intended therefore to provide a greatly improved understanding of the nature, extent, accessibility and sustainability, of some of the UK's potentially substantial and widespread geothermal resources. The research, data and good practice which GGERFS will provide, could greatly assist sustainable development, and community scales of use, of these resources; either on their own or in combination with other sources of heat available above ground, via district heating networks.

GGERFS is located above an extensive network of abandoned mine workings, developed on multiple levels and to significant depths. The mines are all closed now, and when they did, pumping of water ceased and groundwater reverted to natural levels, flooding the mines, creating opportunities for extraction of heat from the minewaters (e.g. PB Power, 2004; Campbell et al. 2010 etc.). This will be a focus of GGERFS research. Sandstones beneath the mine workings also present opportunities for research into their heat potential.

The site therefore has much in common with many towns and villages in Scotland's Central Belt (Figure 1), and elsewhere in the UK with similar mining legacies, and complex Carboniferous geology. Lessons learnt at GGERFS, will be applicable generally across large parts of the UK's former industrial heartlands.

The research focus

The research agenda of GGERFS will be set by the research community as a whole (public and private sectors), with a Science Advisory Group, comprising geothermal and other sub-surface experts, playing a key role. Engagement with, and involvement of the local community will also be crucial. However, the broad focus of GGERFS research will be to investigate heat potential, and the achievable as opposed to the theoretical yield of heat, from:

- warm waters in the abandoned and flooded (coal) mines, up to 300 m below surface; these are aquifers fundamentally affected by mining ("anthropogenically-enhanced aquifers"), and
- strata capable of yielding warm to hot waters (Hot Sedimentary Aquifers (HSA)) at greater depths below the mines (hundreds of metres to more than 1 km).

The potential scale of HSA resources depends largely on natural properties of the host rocks – typically sandstones; depth of occurrence; variable thickness, lateral extent, permeability, porosity, and so productivity.

By contrast, minewater heat resources benefit substantially from their man-made characteristics. Permeability has been greatly increased due to the flow pathways created by layer-parallel galleries of coal workings, connecting tunnels, and shafts, and fractures in the surrounding rocks created by the controlled collapse associated with the prevalent long- and short-wall methods of mining. The enhanced permeability makes water easier to abstract and re-inject, and warmer and cooler waters can likely be kept apart in different levels in the mine, preventing mixing, and sustaining the resource.

Traditionally, geothermal resources have been viewed as sources of heat; with temperatures being either high enough for direct use (similar to water temperatures in current domestic radiators), or sufficiently extreme to enable steam production to power turbines and generate electricity. GGERFS will focus however on geothermal resources at relatively shallow depths. Although of lower temperature, these low enthalpy resources are potentially on a large scale, and relatively more available/accessible. The ability to develop these resources on a small scale at least is already proved. Indeed, a small-scale minewater heat scheme has been operating effectively in the Shettleston area of Glasgow (less than 2km east of GGERFS) for nearly 20 years, and a larger scheme has been operating in the Netherlands (at Heerlen) for 10 years. In addition, the Coal Authority pump waters from mine workings at several locations in the UK to maintain groundwater levels, and abstract heat at some of these. However, the key potential to up-scale schemes such as these, and to sustain flow and productivity of water and heat, and return of cooler waters to the subsurface (using confined open-loop heat pump technology), is still largely unknown, and/or poorly documented, especially in the complex geological and post-industrial environmental conditions which prevail in the UK.

GGERFS is ideally located to address this challenge, as it lies in an area where there is neither active discharge, nor controlled pumping, of the mine waters. Also, as mining ceased 83 years ago, the baseline conditions of the mine waters should be relatively stable (chemistry, temperature, flow, level, etc.), including likely adaptation to the urban heat island effect. Any subsequent changes due to removal/addition of heat should be more readily observable, and monitored over time.

However, there is an even greater opportunity to be explored by GGERFS research; to provide both heating, and cooling to where and when needed, affordably, and ideally in combination with other sources of heat (Figure 1). This would entail developing management of heat sustainably below surface and on appropriate scales, including its storage when there is a surplus (seasonal, daily, operational supply and demand), or when cooling is required, so that peak and continuous demands can be met within and between communities.

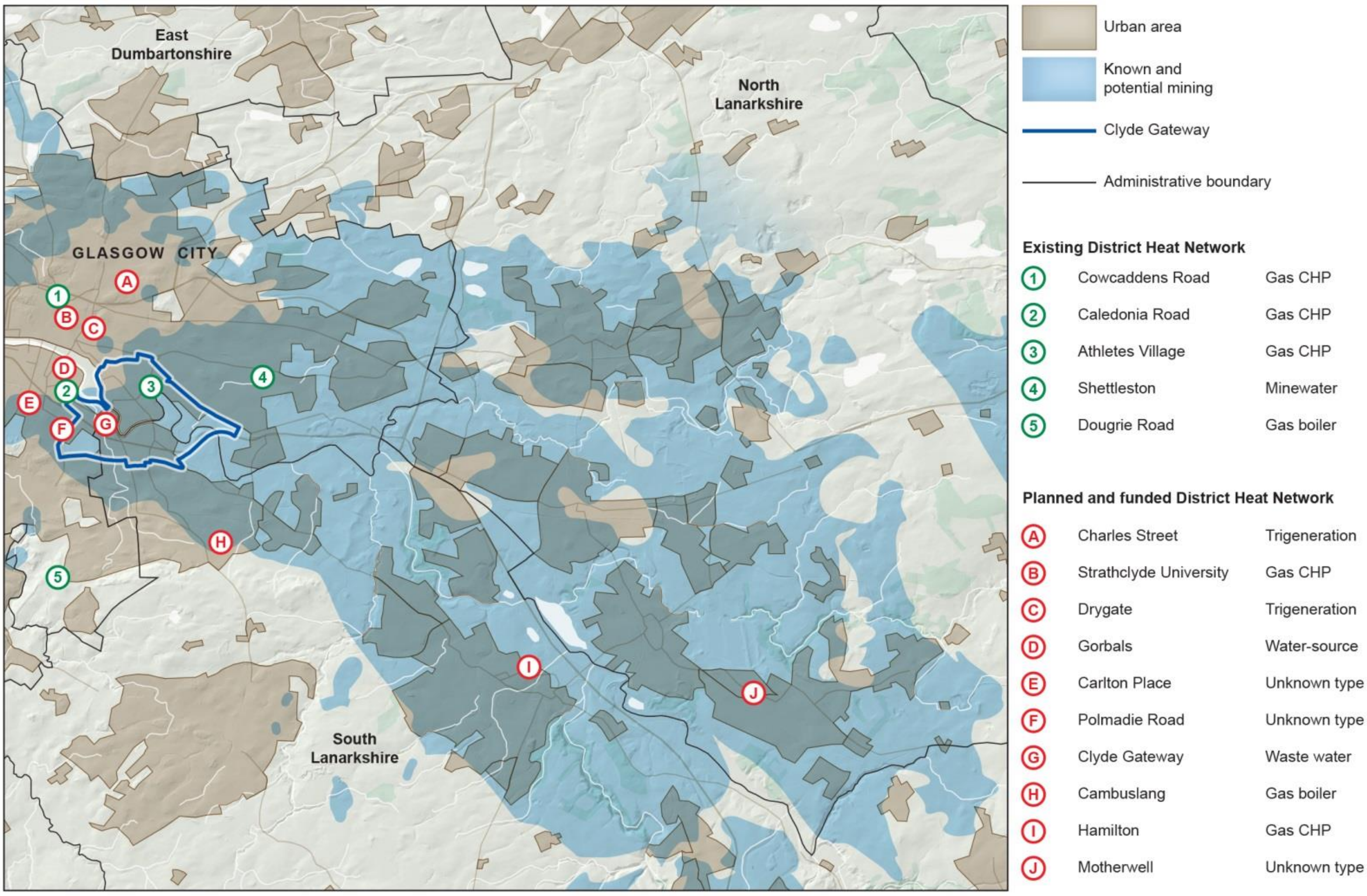


Figure 1 Eastern Glasgow Conurbation: GGERFS site (Clyde Gateway); spatial relationship of known and potential mining and urban areas; and existing/planned district heating networks. Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2017. Licence number 100021290 EUL

Potential scale(s) of heat storage will depend on scales of sub-surface partitioning caused by, for example:

- natural / geological partitioning, due to;
  - faults/fault zones, their later and vertical continuities, and infill, and hence their behaviour as aquicludes, or conduits for flow (or both)
  - dykes which act as aquicludes, and
  - the presence of folds (which plunge and doubly-plunge)
- man-made partitioning, due to;
  - the scale and interconnectedness of the mine workings (the extent of the worked coal seams having been controlled by geological faults but breached by connecting tunnels and shafts).

In addition, there is the exciting possibility of using the existing labyrinth of mine workings, and connecting tunnels and shafts, to transfer heat in a controlled way (the mines acting as arteries for water/heat flow) from areas of relative surplus, to those of need. This could obviate some costly district heating surface infrastructure.

The infrastructure, data and modelling

GGERFS will establish arrays of sensors on surface, boreholes (environmental baseline, characterisation / monitoring wells) and one or more geothermal boreholes into the mine workings. A phased approach of borehole installation will be used to test, model, and predict far-field effects of heat extraction, storage and transfer below ground, and to enable high resolution, dynamic and linked models of heat, flow and mechanical responses, to be developed and validated.

All of the boreholes will be equipped with cutting edge sensors to establish baseline conditions, and support systematic sampling and measurements of, for example: geochemistry (isotopes, dissolved gases, hydrochemistry, trace organics); heat in waters; thermal conductivity; flow of groundwater / minewater; discharges if any (including "diffuse" discharges into superficial deposits, and the Clyde); partitioning, and hydraulic and other properties, and so heat productivity, of the mine workings where different mining techniques were used, and differing waste (goaf) and voids generated.

The geothermal boreholes in particular can:

- Test and optimise new technologies, sensors, performance, and operational strategies
- Carry out chemical and heat tracer tests to refine and calibrate models, and
- Trial and monitor strategies (dosing, dissolved gas management, minimise clogging and performance of heat exchangers and injection wells)

GGREFS can address a host of research challenges, such as:

- development of optimal strategies for cost-effective invasive (drilling and sensoring) and non-invasive (geophysical and remote sensing) geothermal exploration to characterise the mined and deeper sub-surface, including potentially productive sandstones.
- dynamic modelling, and developing related 2D/3D/4D decision-support tools and guidance to optimise:
  - location and spacing of extraction/reinjection systems for, and
  - scales of development and integration of minewater and associated geothermal systems.

Although not directly funded by GGERFS, the facility will also provide excellent opportunities to test and develop aspects of demand-side research, and potential linkages locally and on a wider scale with the many heat related projects, and district heating networks developing in the Glasgow area (Figure 1) (e.g. Kyriakis, 2016). This raises the potential to develop a game-changing, fully operational, integrated, and monitored, above and below ground heat management demonstration project as an exemplar to inspire others.

GGERFS can also provide valuable opportunities to:

- test and extend a BGS (NERC)-Glasgow City Council initiative on planning of Glasgow's sub-surface, avoiding conflicting uses, and stewardship of its sub-surface resources and assets
- develop sub-surface planning of heat resources of varying type, location and depth, extending BGS work on subsurface modelling and uncertainty as the basis for separation zones.
- refine licensing, and exploitation of heat resources to address potential conflicts between neighbouring users related to subsurface heat storage and transfer given potential openness of the minewater system.

References

British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: https://envirolib.apps.nerc.ac.uk/olibcgi.

ANDERSON, E M. 1940. The loss of heat by conduction from the earth's crust in Britain. *Proceedings of the Royal Society of Edinburgh*, 60, 192-209.

ANTONELLINI, M, and AYDIN, A. 1995. Effect of faulting on fluid flow in porous sandstones: Geometry and spatial distribution. *AAPG Bulletin 1995*, 79:5, 642-671.

AYDIN, A. 1978. Small faults formed as deformation bands in sandstone. *Pure and Applied Geophysics*, 116, 913-930.

APPLETON, J D, HOOKER, P J, and SMITH, N J P. 1995. Methane, carbon dioxide and oil seeps from natural sources and mining areas: characteristics, extent and relevance to planning and development in Great Britain. *British Geological Survey.Technical Report* WP/95/1.

ARKLEY, S. 2017 The 3D Quaternary geology of the Clyde Gateway area. British Geological Survey Internal Report, *In review, report number TBC*

BALL D F. 1999. An overview of groundwater in Scotland. *British Geological Survey Technical Report* WD/99/44.

BANKS, D., SKARPHAGEN, H.,WILTSHIRE, R. & JESSOP, C. 2004. Heat pumps as a tool for energy recovery from mining wastes. In: Giere, R. & Stille, P. (eds) Energy, Waste and the Environment: a Geochemical Perspective. Geological Society, London, Special Publications, 236, 499– 513.

BANKS, D. 2009. The operational performance of Scottish minewater-based ground source heat pump systems. *Quarterly Journal of Engineering Geology and Hydrogeology*, 42, 347 – 357.

BANKS, D., FRAGA-PUMAR, A. and, WATSON I. 2009. The operational performance of Scottish minewater-based ground source heat pump systems. *Quarterly Journal of Engineering Geology and Hydrogeology,* 42(3), 347-357.

BAPTIE, B. 2010. Seismogenesis and state of stress in the UK. *Tectonophysics*, 482, 1-4, 150-159.10.1016/j.tecto.2009.10.006

BAPTIE, B. 2012. UK earthquake monitoring 2011/2012: Twenty-third Annual Report. *British Geological Survey Commissioned report,* OR/12/092 (Edinburgh).

BAPTIE, B, SEGOU, M, ELLEN, R, and MONAGHAN, A. 2016. Unconventional Oil and Gas Development: Understanding and Monitoring Induced Seismic Activity. *British Geological Survey Open Report*, OR/16/042. 92pp.

BARTON, C A, ZOBACK, M D, and MOOS, D. 1995. Fluid flow along potentially active faults in crystalline rock. *Geology*, 23, 683-686.

BEACH, A, WELBON, A L, BROCKBANK, P, and MCCALLUM, J E. 1999. Reservoir damage around faults: outcrop examples from the Suez rift. *Petroleum Geoscience*, 5, 109-116.

BENFIELD, A.E. 1939. *Terrestrial heat flow in Great Britain. Proceedings of the Royal Society,* A 173, 430-450.

BENSE, V F, and PERSON, M A. 2006. Faults as conduit-barrier systems to fluid flow in siliciclastic sedimentary aquifers. *Water Resources Research*. W05421.

BENSE, V F, GLEESON, T, LOVELESS, S E, BOUR, O, and SCIBEK, J. 2013. Fault zone hydrogeology. *Earth-Science Reviews*, 127, 171-192.

BERG, S S, and SKAR, T. 2005. Controls on damage zone asymmetry of a normal fault zone: Outcrop analyses of a segment of the Moab fault, SE Utah, *Journal of Structural Geology*, 27, 1803–1822.

BEWLEY, R J F, JEFFERIES, R, WATSON, S, and GRANGER, D. 2001. An overview of chromium contamination issues in the south-east of Glasgow and the potential for remediation. *Environmental Geochemistry and Health*, 23, 267–71.

BEWLEY, RJ F, and SOJKA, G. 2013. In situ deliverability trials using calcium polysulphide to treat chromium contamination at Shawfield, Glasgow. *Technology Demonstration Project Bulletin, 30*. London: Contaminated Land: Applications in Real Environments (CL:AIRE).

BIANCHI, M., KEARSEY, T. AND KINGDON, A. 2015 Integrating deterministic lithostratigraphic models in stochastic realizations of subsurface heterogeneity. Impact on predictions of lithology, hydraulic heads and groundwater fluxes. *Journal of Hydrology*, 531 (3). 557-573. 10.1016/j.jhydrol.2015.10.072

BILLI, A. 2005. Grain size distribution and thickness of breccia and gouge zones from thin strike-slip fault cores in limestone. *Journal of Structural Geology*, 27:10, 1823-1837

BLUCK, B J, GIBBONS, W, and INGHAM, J K, 1992. Terranes. in COPE, J C, INGHAM, J K, RAWSON,P F. (Eds), *Atlas of Palaeogeography and Lithofacies*. Geol. Soc. (London) Memoirs, Vol. 13, pp. 1–4.

BONSOR, H C, and Ó DOCHARTAIGH, B É. 2010. Groundwater monitoring in urban areas - a pilot investigation in Glasgow, UK. *British Geological Survey Internal Report* IR/10/020.

BONSOR H C, BRICKER, S H, Ó DOCHARTAIGH, B É, and LAWRIE, K I G. 2010. Project progress report 2010-11: Groundwater monitoring in urban areas - a pilot study in Glasgow, UK. *British Geological Survey Internal Report* IR/10/087.

BRERETON, R, BROWNE, M A E, CRIPPS, A C, GEBSKI, J S, BIRD, M, HALLEY, D N, and MCMILLAN, A A. 1988. Glenrothes Borehole: Geological Well Completion Report. Investigation of the Geothermal Potential of the UK, British Geological Survey.

BRITISH GEOLOGICAL SURVEY. 1992. Airdrie. Scotland Sheet 31W. Solid Geology. 1:50,000. (Keyworth, Nottingham: British Geological Survey.)

BRITISH GEOLOGICAL SURVEY.1992. Airdrie. Scotland Sheet 31W. Drift Geology. 1:50,000. (Keyworth, Nottingham: British Geological Survey.)

BRITISH GEOLOGICAL SURVEY.1993. Glasgow. Scotland Sheet 30E. Solid Geology. 1:50,000. (Keyworth, Nottingham: British Geological Survey.)

BRITISH GEOLOGICAL SURVEY. 1994. Glasgow. Scotland Sheet 30E. Drift Geology. 1:50,000. (Keyworth, Nottingham: British Geological Survey.)

BRITISH GEOLOGICAL SURVEY. 1995. Glasgow SE. Scotland Sheet NS56SE. Bedrock Geology. 1:10,000. (Keyworth, Nottingham: British Geological Survey.)

BRITISH GEOLOGICAL SURVEY. 2008. Rutherglen. Scotland Sheet NS66SW. Bedrock Geology. 1:10,000. (Keyworth, Nottingham: British Geological Survey.)

BGS. 2016a. Heat Energy Beneath Glasgow. Keyworth: British Geological Survey. http://www.bgs.ac.uk/research/energy/geothermal/heatEnergyGlasgow.htm. Access Date October 2016.

BGS 2016b. Environmental Baseline Monitoring in the Vale of Pickering. Keyworth: British Geological Survey http://www.bgs.ac.uk/research/groundwater/shaleGas/monitoring/yorkshire.html. Access Date November 2016.

BRITISH GEOLOGICAL SURVEY. 2008. Digital Geological Map of Great Britain 1:50 000 scale (DiGMapGB-50) data. Version 5.18. [Keyworth, Nottingham: British Geological Survey]. Release date 20-05-2008.

BRITISH GEOLOGICAL SURVEY. [DIGMAPGB]. 2009. Digital Geological Map of Great Britain 1:10 000 scale (DiGMapGB-10) data. Version 2.18. [Keyworth, Nottingham: British Geological Survey]. Release date 15-01-2009.

BROADWAY, A, CAVE, M R, WRAGG, J, FORDYCE, F M, BEWLEY, R J F, GRAHAM, M C, NGWENYA, B T, and FARMER, J G, 2010. Determination of the bioaccessibility of chromium in Glasgow soil and the implications for human health risk assessment. *Science of the Total Environment*, 409:2, 267-277.

BROWNE, M A E, HARGREAVES, L, and SMITH, I F. 1985. The Upper Palaeozoic basins of the Midland Valley of Scotland. Investigation of the Geothermal Potential of the UK. Keyworth, Nottingham. British Geological Survey.

BROWNE, M A E, DEAN, M T, HALL, I H S, MCADAM, A D, MONRO, S K, and CHISHOLM, J I. 1999. A lithostratigraphical framework for the Carboniferous rocks of the Midland Valley of Scotland. *British Geological Survey Research Report* RR/99/07.

BROWNE, M A E, ROBINS, N S, EVANS, R B, MONRO, S K, and ROBSON, P G. 1987. The Upper Devonian and Carboniferous sandstones of the Midland Valley of Scotland. Investigation of the geothermal potential of the UK. Keyworth. Nottingham: British Geological Survey.

BROWNE, M A E, and MCMILLAN, A A. 1989. Quaternary geology of the Clyde Valley. *British Geological Survey Research Report* SA/89/1.

BURLEY, A.J., EDMUNDS, W.M. and GALE, I N. 1984. *Investigation of the geothermal potential of the UK : catalogue of geothermal data for the land area of the United Kingdom.* Br*itish Geological Survey, 161pp. (WJ/GE/84/020) (Unpublished)*

BURZYNSKI, R. 2008. Assessment of Mine water potential in UK. Report prepared for: Minewater Project, 4 December 2008, Client report number 1.

BUSBY, J, KINGDON, A, and WILLIAMS, J, 2011. The measured shallow temperature field in Britain. *Quarterly Journal of Engineering Geology and Hydrogeology*, 44:3, 373-387.

BUSBY, J, GILLESPIE, M, and KENDER, S. 2015. How hot are the Cairngorms? *Scottish Journal of Geology*, 51, 105-115.

CAINE, J S, EVANS, J P, and FORSTER, C B. 1996. Fault zone architecture and permeability structure. *Geology*, 24:11, 1025-1028.

CAMPBELL, S D G, MONAGHAN A A, ENTWISLE, D C, MERRITT. J E, BROWNE, M A E. 2008. Geoscience for decision making. *GeoConnexion UK*, Vol 6, pt 1, pg 22-23.

CAMPBELL, DIARMAD, CRANE, EMILY, O DOCHARTAIGH, BRIGHID, LAWRENCE, DAVE, BUSBY, JON, MCCORMAC, MIKE, MONAGHAN, ALISON, MCLEAN, BILL, HULBERT, ANDY. 2010 Future energy. *Earthwise*, 26, 34-35

CAMPBELL, S D G, MERRITT, J E, Ó DOCHARTAIGH, B E, MANSOUR, M, HUGHES, A G, FORDYCE, F M , ENTWISLE, D C, MONAGHAN, A A, LOUGHLIN, S C. 2010. 3D modelling and related datasets for Urban Development - A case study in Glasgow-Clyde, UK 3D geological models and their hydrogeological applications : supporting urban development : a case study in Glasgow-Clyde, UK in *Zeitschrift der Deutschen Gesellschaft fur Geowissenschaften*, Vol. 161 pt/no 2, 251-262

CHOI, J H, EDWARDS, P K,YOUNGTAE, K, and YOUNG-SEOG, K. 2016. Definition and classification of fault damage zones: A review and a new methodological approach. *Earth-Science Reviews*, 152, 70-87.

CLOUGH, C T, HINXMAN, L W, WRIGHT, W B, ANDERSON, E M, and CARRUTHERS, R G. 1926. The economic geology of the Central Coalfield of Scotland, description of area V, Glasgow East, Coatbridge and Airdrie. *Memoir of the Geological Survey of Scotland.*

CEC. 2008. Directive 2008/105/EC on Environmental Quality Standards in the Field of Water Policy. Brussels: Council of the European Community.

CCME. 2011. Canadian water quality guidelines for the protection of aquatic life: Uranium. In: *Canadian Environmental Quality Guidelines*. Winnipeg: Canadian Council of Ministers of the Environment: Winnipeg.

CL:AIRE. 2010. *Soil Generic Assessment Criteria for Human Health Risk Assessment*. London: Contaminated Land: Applications in Real Environments.

DEFRA. 2014. *Development of Category 4 Screening Levels for Assessment of Land Affected by Contamination. Policy Companion Docu+ment SP1010. London*: Department for Environment, Food and Rural Affairs.

DOWNING, R A, and GRAY, D A. 1986. Geothermal resources of the United Kingdom, *Journal of the Geological Society*, 143(3), 499-507.

EA (ENVIRONMENT AGENCY). 2002. *Contaminated Land Exposure Assessment Soil Guideline Values*. Bristol: Environment Agency.

EA (ENVIRONMENT AGENCY) 2009. *Contaminated Land Exposure Assessment Soil Guideline Values*. Bristol: Environment Agency. https://www.gov.uk/government/publications/land-contamination-soil-guideline-values-sgvs Access date January 2015.

EA (ENVIRONMENT AGENCY) 2013. *River Water Classifications*. Bristol: Environment Agency. Access date February 2013. http://www.environment-agency.gov.uk/research/planning/34383.aspx

ELLEN, R, LOVELESS, S, and BARRON, H F. 2015. South Seeds renewable heat: Potential mine water heat recovery in the South Side of Glasgow. *British Geological Survey Commissioned Report* CR/15/084.

ELLEN, R, and LOVELESS, S. 2015. Potential mine water heat recovery at Hartwood Home Farm, North Lanarkshire. B*ritish Geological Survey Commissioned Report*, CR/15/131.

FARMER, J G, GRAHAM, M C, THOMAS, R P, LICONA-MANZUR, C, PATERSON, E, CAMPBELL, C D, GEELHOED, J S, LUMSDON, D G, MEEUSSEN, J C L, ROE, M J, CONNER, A, FALLICK, A E, and BEWLEY, R J F. 1999. Assessment and modelling of the environmental chemistry and potential for remediative treatment of chromium-contaminated land. *Environmental Geochemistry and Health*, 21, 331-337.

FARMER J G, THOMAS R P, GRAHAM M C, GEELHOED J S, LUMSDON D G and PATERSON E. 2002. Chromium speciation and fractionation in ground and surface waters in the vicinity of chromite ore processing residue disposal sites. *Journal of Environmental Monitoring* 4, 235-243.

FINLAYSON, A, MERRITT, J, BROWNE, M, MERRITT, J E, MCMILLAN, A, and WHITBREAD, K. 2010. Ice sheet advance, dynamics, and decay configurations: evidence from west central Scotland. *Quaternary Science Reviews*, Vol. 29, 969-988

FORDYCE, F M, Ó DOCHARTAIGH, B É, LISTER, T R, COOPER, R, KIM, A, HARRISON, I, VANE, C, and BROWN, S E. 2004. Clyde Tributaries: Report of Urban Stream Sediment and Surface Water Geochemistry for Glasgow. *British Geological Survey Commissioned Report* CR/04/037. http://nora.nerc.ac.uk/18996/

FORDYCE, F M, and Ó DOCHARTAIGH B É. 2010. Developments to GRASP 2009/10. GRASP: a GIS tool to assess pollutant threats to shallow groundwater in the Glasgow area. *British Geological Survey Internal Report* IR/10/034

FORDYCE, F M, NICE, S E, LISTER, T R, Ó DOCHARTAIGH, B É, COOPER, R, ALLEN, M, INGHAM, M, GOWING, C, VICKERS, B P, and SCHEIB, A. 2012. Urban Soil Geochemistry of Glasgow. *British Geological Survey Open Report* OR/08/002. http://nora.nerc.ac.uk/18009/

FORDYCE, F M, BONSOR, H C, and Ó DOCHARTAIGH, B É. 2014. Developments to GRASP 2012/13. GRASP: a GIS tool to assess pollutant threats to shallow groundwater in the Glasgow area. *British Geological Survey Internal Report*, IR/13/024.

FORSYTH, I H, HALL, I H S, MCMILLAN, A A, ARTHUR, M J, BRAND, P J, GRAHAM, D K, and ROBINS, N S. 1996. Geology of the Airdrie district: *Memoir of the British Geological Survey*, Sheet 31W (Scotland). ISBN 011884508X

FOSSEN, H, and HESTHAMMER, J. 2000. Possible absence of small faults in the Gullfaks Field, northern North Sea: Implications for downscaling of faults in some porous sandstones, *Journal of Structural Geology*, 22(7), 851–863

FRAGA PUMAR A. 2007. Sustainability of mine water based ground source heating schemes. MSc Thesis, University of Newcastle

GALLOWAY, D, BUKITS, J, and FORD, G. 2013. Bulletin of British Earthquakes 2012. *British Geological Survey Seismological Report*, OR/13/54.

GIBSON, R. G. 1998. Physical character and fluid-flow properties of sandstone-derived fault zones. *Geological Society, London*, Special Publications. 127(1), 83-97.

GLASGOW CITY ARCHIVES. 2016. The Glasgow Story. http://www.theglasgowstory.com/. Access Date June 2016.

GREGORY, J. 1911. The Glasgow earthquake on 14th December, 1910. *Transactions of the Geological Society of Glasgow*, Vol. 14, 90-114.

GILLESPIE, M R, CRANE, E J, and BARRON, H F. 2013. Study into the Potential for Deep Geothermal Energy in Scotland: Volume 2. *British Geological Survey Commissioned Report,* CR/12/131 Scottish Government Project Number AEC/001/11. ISBN: 9781782569862 (web only publication)

GOODLET, G A. 1957. Lithological variation in the Lower Limestone Group in the Midland Valley of Scotland. *Bulletin of the Geological Survey of Great Britain*, Vol. 12, 52-65.

HALL, I H S, BROWNE, M A E, and FORSYTH, I H. 1998. Geology of the Glasgow district. *Memoir of the British Geological Survey,* Sheet 30E (Scotland). ISBN 0-11-884534-9.

HILLIER, S, ROE, M J, GEELHOED, J S, FRASER, A R, FARMER, J G, and PATERSON, E. 2003. Role of quantitative mineralogical analysis in the investigation of sites contaminated by chromite ore processing residue. *Science of the Total Environment*, 308, 195-200.

HINXMAN, L W, ANDERSON, E M, and CARRUTHERS, R G. 1920.The economic geology of the Central Coalfield of Scotland, Area IV, Paisley, Barrhead and Renfrew. *Memoir of the Geological Survey*, Scotland.

HMSO. 1990. Environmental Protection Act Part IIa. Contaminated Land. London: HSMO.

HOOPER, M. 2003. The Carboniferous evolution of the Central Coalfield Basin, Midland Valley of Scotland: implications for basin formation and the regional tectonic setting. Unpublished PhD thesis, University of Leicester.

HOUGH, E, BURKE, S, WATSON, C AND DEARDEN, R. 2017. ESIOS Platform - Thornton Detailed project plan 2017/18. British Geological Survey Internal Report, IR/17/033. 95pp

INAP. 2009. Global Acid Rock Drainage Guide (GARD Guide). The International Network for Acid Prevention. http://www.gardguide.com. Access Date November 2016.

JONES, D G, LISTER, T R, STRUTT, M H, ENTWISLE, D C, HARRISON, I, KIM, A W, RIDGWAY, J, and VANE, C H. 2004. Estuarine Geochemistry: Report for Glasgow City Council. *British Geological Survey Commisioned Report* CR/04/057.

KEARSEY T I, WHITBREAD K, ARKLEY S L B, FINLAYSON A, MONAGHAN A A, MCLEAN W S, TERRINGTON R L, CALLAGHAN E, MILLWARD D AND CAMPBELL S D G. In press. Creation and delivery of a complex 3D geological survey for the Glasgow area and its application to urban geology. Earth and Environmental Science: *Transactions of the Royal Society of Edinburgh*

KEARSEY, T., WILLIAMS, J., FINLAYSON, A., WILLIAMSON, P., DOBBS, M., MARCHANT, B., KINGDON, A. & CAMPBELL, S.D. 2015 Testing the application and limitation of stochastic simulations to predict the lithology of glacial and fluvial deposits in Central Glasgow, UK. Engineering Geology, 187. 98 - 112. 10.1016/j.enggeo.2014.12.017

KEARSEY, T. 2017. Model metadata report for Glasgow Geothermal Energy Research Field Site Bedrock Model. British Geological Survey Open Report, OR/17/044, *in review*

KESSLER, H, MATHERS, S J, SOBISCH, H-G, and NEBER, A.2008. GSI3D – The software and methodology to build systematic near-surface 3-D geological models. (Version 2) British *Geological Survey Open Report*, OR/08/001 144pp.

KIM, AW, VANE, C H, MOSS-HAYES, V L, BERIRO, D J, NATHANAIL, C P, FORDYCE, F M, and EVERETT, P A. In Press. Polycyclic aromatic hydrocarbons (PAH) and polychlorinated biphenyls (PCB) in urban soils of Glasgow, UK. Earth and Environmental Science: *Transactions of the Royal Society of Edinburgh*

KINGDON, A, FELLGETT, M W, AND WILLIAMS, J D O. 2016. Use of borehole imaging to improve understanding of the in-situ stress orientation of Central and Northern England and its implications for unconventional hydrocarbon resources. *Marine and Petroleum Geology*, Vol. 73 May 2016, Pages 1–20. DOI: 10.1016/j.marpetgeo.2016.02.012

KNIPE, R J. 1997. Juxtaposition and seal diagrams to help analyze fault seals in hydrocarbon reservoirs. *AAPG Bulletin*, 87:2, 187-195.

KNOTT, S.D., BEACH A., BROCKBANK, P.J., BROWN, J.L., MCCALLUM J.E. & WELBON A.I. 1996 Spatial and mechanical controls on normal fault populations, Journal of Structural Geology, 18, 359-372, ISSN 0191-8141, http://dx.doi.org/10.1016/S0191-8141(96)80056-3

KYRIAKIS, S. 2016. Geothermal district heating networks: modelling novel operational strategies incorporating heat storage. PhD Thesis, University of Glasgow

LEE, M K, WHEILDON, J, WEBB, P C, BROWN, G C, ROLLIN, K E, CROOK, C N, SMITH, I F, KING, G, and THOMAS-BETTS, A. 1984. Hot dry rock prospects in Caledonian Granites:evaluation of results from the BGS-IC-OU research programme (1981-1984). Report in series: *Investigation of the Geothermal Potential of the UK*. (Keyworth, Nottingham: British Geological Survey.)

LEE, M, BROWN, G, WEBB, P, WHEILDON, J, and ROLLIN, K. 1987. Heat flow, heat production and thermo-tectonic setting in mainland UK. *Journal of the Geological Society*, 144(1), 35-42.

LOFTUS, G W F, and GREENSMITH, J T. 1988. The lacustrine Burdiehouse Limestone Formation—a key to the deposition of the Dinantian Oil Shales of Scotland. *Geological Society, London*, Special Publications, 40, 219-234.

MACDONALD, D D, INGERSSOLL, C G, and BERGER, T A. 2000. Development and evaluation of consensus-based sediment quality guidelines for freshwater ecosystems. *Archives of Environmental Contamination and Toxicology*, 39, 20–31.

MCMILLAN, A, and POWELL, J. 1999. BGS Rock Classification Scheme. Volume 4, classification of artificial (man-made) ground and natural superficial deposits: applications to geological maps and datasets in the UK. *British Geological Survey Research Report* RR/99/004.

MACNAB, J D. 2011. A review of the potential thermal resource in Glasgow's abandoned coal mine workings. MSc Thesis, University of Strathclyde.

MERRITT, J E, MONAGHAN, A A, ENTWISLE, D C, HUGHES, A G, CAMPBELL, S DG, and BROWNE, M A E. 2007. 3D attributed models for addressing environmental and engineering geoscience problems in areas of urban regeneration – a case study in Glasgow, UK. *First Break*, 25, 79-84

MERRITT, J E, MONAGHAN, A A, LOUGHLIN, S C, MANSOUR, M, Ó DOCHARTAIGH, B É, and HUGHES A G. 2009. Clyde Gateway Pilot 3D Geological and Groundwater Model. *British Geological Survey Commissioned Report*, CR/09/005.

MICARELLI, L, BENEDICTO, A, and WIBBERLEY, C A J. 2006. Structural evolution and permeability of normal fault zones in highly porous carbonate rocks. *Journal of Structural Geology*, 28:7, 1214-1227.

MICARELLI , L, BENEDICTO, A, and WIBBERLEY, C A. 2006. Uplift, deformation and fluid involvement within an active normal fault zone in the Gulf of Corinth, Greece. *Journal of the Geological Society*; 151:3, 1214-1227.

MILODOWSKI, A E, and RUSHTON, J E. 2008. Mineralogical and porosity characterisation of potential aquifer and seal units for carbon capture and storage methodologies for the CASSEM Project. *British Geological Survey Commissioned Report*, CR/08/153. 86pp.

MONAGHAN, A A, TERRINGTON, R L, and MERRITT , J E. 2012. Clyde Gateway Pilot 3D Geological Model, Version 2. *British Geological Survey Commissioned Report*, CR/12/010. 10pp

MONAGHAN, A A. 2012a. Model metadata report for the Clyde Gateway v2 bedrock model. *British Geological Survey Internal Report*, IR/12/006.39pp.

MONAGHAN, A A, ARKLEY, S L B, WHITBREAD, K, and MCCORMAC, M. 2013. Clyde superficial deposits and bedrock models released to the ASK Network 2013 : a guide for users Version 2. *British Geological Survey Open Report*, OR/13/025.35pp.

MONAGHAN, A A, BROWNE, M A E, and BARFOD, D N. 2014 An improved chronology for the Arthur's Seat Volcano and Carboniferous magmatism of the Midland Valley of Scotland. *Scottish Journal of Geology,* Vol. 50, 165-172.

MOOS, D, and ZOBACK, M D. 1990. Utilization of observations of well bore failure to constrain the orientation and magnitude of crustal stresses: application to continental, Deep Sea Drilling Project, and Ocean Drilling Program boreholes. *Journal of Geophysical Research*, 95, 9305–9325.

MUSSON, R M W, NEILSON, G, and BURTON, P W. 1984. Macroseismic reports on historical British earthquakes III: Central and West Scotland. *British Geological Survey Report,* 209.

MUSSON, R M W. 1989. Seismicity of Cornwall and Devon. *British Geological Survey Global Seismology Report*, WL/89/11 (Edinburgh).

MUSSON, R M W. 1994. A catalogue of British earthquakes. *British Geological Survey Global Seismology Report*, WL/94/04.

MUSSON, R M W.1996. The seismicity of the British Isles. *Annali di Geofisica*, Vol. 39, 463-469.

MUSSON, R M W. 2004. A critical history of British earthquakes. *Annals of Geophysics*, Vol. 47, 597-610.

MUSSON, R M W. 2007. British earthquakes. *Proceedings of the Geologists' Association*, Vol. 118, 305-337.

NATHANAIL, C P, MCCAFFREY, C, GILLETT, A G, OGDEN, R C, and NATHANAIL, J F. 2015. *The LQM/CIEH S4ULs for Human Health Risk Assessment*. Nottingham: Land Quality Press. Copyright Land Quality Management Limited reproduced with permission Publication Number S4UL3083. All rights reserved.

NEILSON, G, MUSSON, R M W, and BURTON, P W. 1984. Macroseismic reports on historical British earthquakes V: The South and South West of England. *British Geological Survey Global Seismology Report, No 231* (Edinburgh).

Ó DOCHARTAIGH B É. 2005. Review of hydrogeological knowledge of the Clyde Basin. *British Geological Survey Internal Report* IR/05/079.

Ó DOCHARTAIGH, B É, BALL, D F, MACDONALD, A M, LILLY, A, FITZSIMONS V, DEL RIO, M, and AUTON, C A. 2005. Mapping groundwater vulnerability in Scotland: a new approach for the Water Framework Directive. *Scottish Journal of Geology*, 41:1, 21-30.

Ó DOCHARTAIGH, B É, GRAHAM, M T, and MACDONALD, A M. 2007. A summary of groundwater work within the Clyde Basin project, 2005-06. *British Geological Survey Internal Report* IR/07/042.

Ó DOCHARTAIGH, B É. 2009. Groundwater research needs in Glasgow and the Clyde Basin, *British Geological Survey Internal Report* IR/09/036.

Ó DOCHARTAIGH, B É, SMEDLEY, P L, MACDONALD, A M, DARLING, W G, and HOMONCIK, S. 2011. Baseline Scotland: groundwater chemistry of the Carboniferous sedimentary aquifers of the Midland Valley. *British Geological Survey Open Report* OR/11/021.

Ó DOCHARTAIGH, B.E.; MACDONALD, A.M.; FITZSIMONS, V.; WARD, R.. 2015 *Scotland's aquifers and groundwater bodies.* Nottingham, UK, British Geological Survey, 63pp. (OR/15/028)

Ó DOCHARTAIGH B, BONSOR H AND BRICKER S. In review. The Quaternary groundwater system in Glasgow. *Earth and Environmental Science: Transactions of the Royal Society of Edinburgh*

OTHIENO, R. (2016). Gorebridge CO_2 incident. Oral Presentation. Scottish Health Protection Network Symposium. Golden Jubilee Conference Centre, Clydebank 29 November 2016.

PALUMBO-ROE, B, BANKS, V J, BONSOR, H C, WATTS, M C, HAMILTON, E M, and CHENERY, S. 2013. Mobility of chromium in the hyporheic zone of an urban stream. *Proceedings of the 7th International Workshop on Chemical Bioavailability*, Nottingham 3-6 Nov 2013.

P B POWER. 2004. Shawfair Minewater Project: Scottish National Minewater Potential Study. Job No. 69211a/001

PENN, I E, SMITH, I F, AND HOLLOWAY, S. 1984. Interpretation of a deep seismic reflection profile in the Glasgow area.

PHE. 2016. UK Radon. Public Health England. http://www.ukradon.org/. Access Date October 2016.

PHE-BGS. 2011. Indicative Atlas of Radon in Scotland. Report HPA-CRCE-023. Didcot: Public Health England.

READ, W A. 1988a. Controls on Silesian sedimentation in the Midland Valley of Scotland. *In*: Besly, B.M., Kelling, G. (eds) *Sedimentation in a synorogenic basin complex: the Upper Carboniferous of northwest Europe*. Blackie and Son, Glasgow. 222–241.

READ W A. 1988b. The interplay of sedimentation, volcanicity and tectonics in the Passage Group (Arnsbergian, E2 to Westphalian A) in the Midland Valley of Scotland. *In:* ARTHURTON, R S, GUTTERIDGE, P, and NOLAN, S C. (eds) *The*

Role of Tectonics in Devonian and Carboniferous Sedimentation in the British Isles. Occasional Publications of the Yorkshire Geological Society, 6, 143-152.

READ, W A. 1989. Sedimentological evidence for a major subsurface fracture system linking the eastern Campsie and the eastern Ochil faults. *Scottish Journal of Geology*, 25,187-200.

READ W A. 1994. High frequency glacial-eustatic sequences in early Namurian coal-bearing fluviodeltaic deposits, central Scotland. *Spec Publ. Int Ass Sediment*., 19, 413-428.

READ, W A, BROWNE, M A E, STEPHENSON, D, and UPTON, B J G. 2002. Carboniferous. In: Trewin N.H. (ed) The Geology of Scotland. Fourth Edition. The Geological Society, London, 251-300.

REINECKER, J, TINGAY, M, and MÜLLER, B, 2003. Borehole breakout analysis from four-arm caliper logs, World Stress Map Project. WSM website: http://dcapp314.gfzpotsdam.de/pub/guidelines/WSM_analysis_guideline_breakout_caliper.pdf

ROBINS, N S. 1986. Groundwater chemistry of the main aquifers in Scotland. *British Geological Survey Report* 18, No. 2. ISBN 0-11-884380-X.

ROBINS, NS, and BROWNE, M A E. 1987. The modelling of groundwater flow patterns in the Upper Palaeozoic coal basins of the Midland Valley of Scotland. *Transactions of International Symposium on Hydrogeology of Coal Basins, Katowice, Poland*, 477-484

ROBINS, NS, 1988. Hydrogeological map of Scotland. 1:625 000

ROBINSON, N, and GRAYSON, R. 1990. Natural methane seepages in the Lanarkshire Coalfield. *Land and Minerals Surveying*, 8, 333-340.

ROLLIN, K E. 1987. Catalogue of geothermal data for the land area of the United Kingdom. Third revision: April 1987. Investigation of the geothermal potential of the UK, British Geological Survey, Keyworth.

SAVAGE, H M, and BRODSKY, E E, 2011. Collateral damage: Evolution with displacement of fracture distribution and secondary fault strands in fault damage zones. *Journal of Geophysical Research*, 116, BO3405.

SCHOLZ, C H. 2002. *The Mechanics of Earthquakes and Faulting*, Cambridge University Press, Cambridge, U.K.

SHIPTON, Z K, and COWIE, P A. 2001. Damage zone and slip surface evolution over μm to km scales in high-porosity Navajo sandstone, Utah. *Journal of Structural Geology*, 23, 1825-1844.

SHIPTON, Z K, SODEN, A M, KIRKPATRICK, J D, BRIGHT, A M, and LUNN, R J. 2006. How thick is a fault? Fault- displacement-thickness scaling revisited, in *Earthquakes: Radiated Energy and the Physics of Faulting, Geophysical Monograph Series*, 170, edited by R. E. Abercrombie et al., 193–198 AGU, Washington, D.C.

SIM, G, GRAHAM, M C, NGWENYA, BT, PALUMBO-ROE, B, and FORDYCE, F M. 2015. Understanding chromium speciation and mobility in urban-industrial environments. *Abstracts of the 8th Scottish Symposium on Environmental Analytical Chemistry*, Glasgow, 9 December 2015.

SMEDLEY, P L, WARD, R S, ALLEN, G, BAPTIE, B, DARAKTCHIEVA, Z, JONES, D G, JORDAN, C J, PURVIS, R M, and Cigna F. 2015. Site selection strategy for environmental monitoring in connection with shale-gas exploration: Vale of Pickering, Yorkshire and Fylde, Lancashire. *British Geological Survey Open Report* OR/15/067.

SMITH, M, LAWRENCE, D, MCINROY, D, MONAGHAN, A, EDWARDS, M, NAYLOR, M, FORD, J, and BRICKER S. 2011. Chapter 3 Defining the Store; Geological Interpretation and storage modelling. in Smith, M. Campbell, D, Mackay, E, and Polson, D, (Eds). CO2 Aquifer Storage Site Evaluation and Monitoring (CASSEM). Heriot-Watt University, Edinburgh. ISBN 978-0-9571031-0-8

TINGAY, M, HILLIS, R R, MORLEY, C K, SWARBRICK, E C, and OKPERE, E C. 2003. Variation in vertical stress in the Baram Basin Brunei: tectonic and geomechanical implications. *Marine and Petroleum Geology,* 20, 1201-1212.

TINGAY, M., REINECKER, J, and MÜLLER, B. 2008. Borehole breakout and drilling-induced fracture analysis from image logs [online], in World Stress Map Project—Guidelines: Image Logs, Helmholtz Cent. Potsdam, GFZ German Research Centre for Geosciences, Potsdam, Germany. (Available at: http://dc-app3-14.gfz-potsdam.de/pub/guidelines/WSM_analysis_guideline_breakout_image.pdf).

TURNER, R. J., MANSOUR, M.M., DEARDEN, R., O DOCHARTAIGH B.E. AND HUGHES A.G. 2015. Improved understanding of groundwater flow in complex superficial deposits using three-dimensional geological-framework and groundwater models: an example from Glasgow, Scotland (UK). *Hydrogeology Journal* Vol 23 (3), 493-506

UNDERHILL, J R, MONAGHAN, A A, and BROWNE, M A E. 2008. Controls on structural styles, basin development and petroleum prospectivity in the Midland Valley of Scotland. *Journal of Marine and Petroleum Geology*, 25,1000-1022

UKTAG. 2008. Proposals for Environmental Quality Standards for Annex VIII Substances. UK Technical Advisory Group on the Water Framework Directive.

VERHOEVEN, R, WILLEMS, E, HARCOUËT-MENOU, V, DE BOEVER, E, HIDDES, L, OP'T VELD, P. and DEMOLLIN, E. 2014. Minewater 2.0 project in Heerlen the Netherlands: transformation of a geothermal mine water pilot project into a full scale hybrid sustainable energy infrastructure for heating and cooling. *Energy Procedia*, 46, pp.58-67.

VERWEIJ, J M, BOXEM, T A P, and NELSKAMP, S. 2016. 3D spatial variation in vertical stress in on- and offshore Netherlands; integration of density log measurements and basin modeling results. *Marine and Petroleum Geology*. DOI: 10.1016/j.marpetgeo.2016.06.016

WESTAWAY, R, and YOUNGER, P L.2013. Accounting for palaeoclimate and topography: a rigorous approach to correction of the British geothermal dataset. *Geothermics*, 48, 31-51.

WHALLEY, C, HURSTHOUSE, A, ROWLATT, S, IQBAL-ZAHID , P, VAUGHAN, H, and DURANT, R. 1999. Chromium speciation in natural waters draining contaminated land, Glasgow, UK. *Water, Air and Soil Pollution*, 112, 389-405.

WHEILDON, J, KING, G, CROOK, C N, and THOMAS-BETTS, A.1984. The Eastern Highlands granites: heat flow, heat production and model studies. Report in series: Investigation of the Geothermal Potential of the UK. British Geological Survey.

WHEILDON, J, and ROLLIN, K E. 1986. Heat Flow. In: Downing, R.A. and Gray, D.A. (Eds), Geothermal Energy – the potential in the United Kingdom. The British Geological Survey, NERC. London: Her Majesty's Stationery Office.

WILLIAMS, J D O, FELLGETT, M W, KINGDON, A , and WILLIAMS, P J. 2015. In-situ stress orientations in the UK Southern North Sea: Regional trends, deviations and detachment of the post- Zechstein stress field. *Marine and Petroleum Geology*. DOI:10.1016/j.marpetgeo.2015.06.008

WILLIAMS, J D O, FELLGETT, M W, and QUINN, M F. 2016. Carbon dioxide storage in the Captain Sandstone aquifer: determination of in situ stresses and fault-stability analysis. *Petroleum Geoscience*, Vol. 22, 211-222. DOI: 10.1144/petgeo2016-036

WILSON, R.B. 1989. A study of the Dinantian marine macrofossils of central Scotland. *Transactions of the Royal Society of Edinburgh*, Earth Sciences, 80, 91-126

WILLIAMS, J.D.O., DOBBS, M.R., KINGDON, A., LARK, R.M., WILLIAMSON, J.P., MACDONALD, A.M. AND Ó DOCHARTAIGH, B.É . In review. Stochastic modelling of hydraulic conductivity derived from geotechnical data: an example applied to Central Glasgow. Earth and Environmental Science: *Transactions of the Royal Society of Edinburgh*

YIELDING, G B, FREEMAN, B, and NEEDHAM, T. 1997. Quantitative fault seal prediction. *AAPG Bulletin,* 81:6, 897-917

YOUNGER, P L, and ROBINS, N S. 2002. Challenges in the characterisation and prediction of the hydrogeology and geochemistry of mined ground. 1-16 in Mine Water Hydrogeology and Geochemistry. Younger PL and Robins NS (editors). Geological Society of London Special Publication, No. 198.

ZOBACK, M D, BARTON, C A, et al. 2003. Determination of stress orientation and magnitude in deep wells. *International Journal of Rock Mechanics and Mining Sciences*, 40, 1049–1076.