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Engineering geology and geotechnical summary of central Glasgow in the vicinity of the UK Geoenergy Observatories field sites

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Engineering geology and geotechnical summary of central Glasgow in the vicinity of the UK Geoenergy Observatories field sites

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Foreword

This report is the published product of a study by the British Geological Survey (BGS) of the engineering and geotechnical properties of the geological units that will be encountered in the Glasgow UK Geoenergy Observatories (UKGEOS) site and environs, Glasgow. The data presented is from a wider area due to the lack of data near the UKGEOS site locations The information presented is a part of the geological characterisation used to inform the drilling and other activities associated with these sites.

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Summary

This report presents the engineering and geotechnical properties of the geological units that will be encountered in the Glasgow UK Geoenergy Observatories (UKGEOS) site and environs, Glasgow. The data is from third party ground investigations provided by client, consultants and contractors. The data is extracted from analogue reports (paper or pdf files) or is 'downloaded' from Association of Geotechnical and Geoenvironmental Specialist (AGS) data transfer file and stored in the BGS National Geotechnical Properties Database from where it was accessed. As there is limited data nearby the proposed UKGEOS sites the data is from a wider area most notably for the deeper bedrock.

The first part of the report briefly introduces the UKGEOS project and the context of this report. Section 2 shows where the UKGEOS site locations and the target formation for the low enthalpy energy. Section 3 gives the borehole locations of the different parameters. Section 4 is about the engineering geology of the different geological units and includes engineering descriptions, various graphs of the different geotechnical parameters and gives a brief interpretation of the data.

1 Introduction

The UKGEOS Glasgow project will provide research infrastructure to investigate the sustainable exploitation of low enthalpy (low temperature) geothermal heat from flooded mine workings. Ground investigations are planned to characterise and monitor the top approximately 200 metres of the subsurface. Interconnected flow systems suitable for large- scale heat recovery may be present in areas of collapsed mines and mine waste where coal seams of more than 1 m thick have been totally extracted, and/or in areas of stoop and room (pillar and stall) workings that are open and flooded.

This report provides the engineering geology and geotechnical characteristics of the units that are modelled to be intercepted by the UKGEOS Glasgow project boreholes. The units included are those identified in the borehole prognoses in five locations sited in the Clyde Gateway development area near the River Clyde, with the additional superficial units that have been modelled nearby. The lowest unit that will be intercepted is the Scottish Lower Coal Measures Formation.

2 Borehole sites

There are five locations currently planned (October 2018). All are within Clyde Gateway regeneration area, which is south-east of the centre of Glasgow, and is on both sides of the River Clyde (see Figure 1).

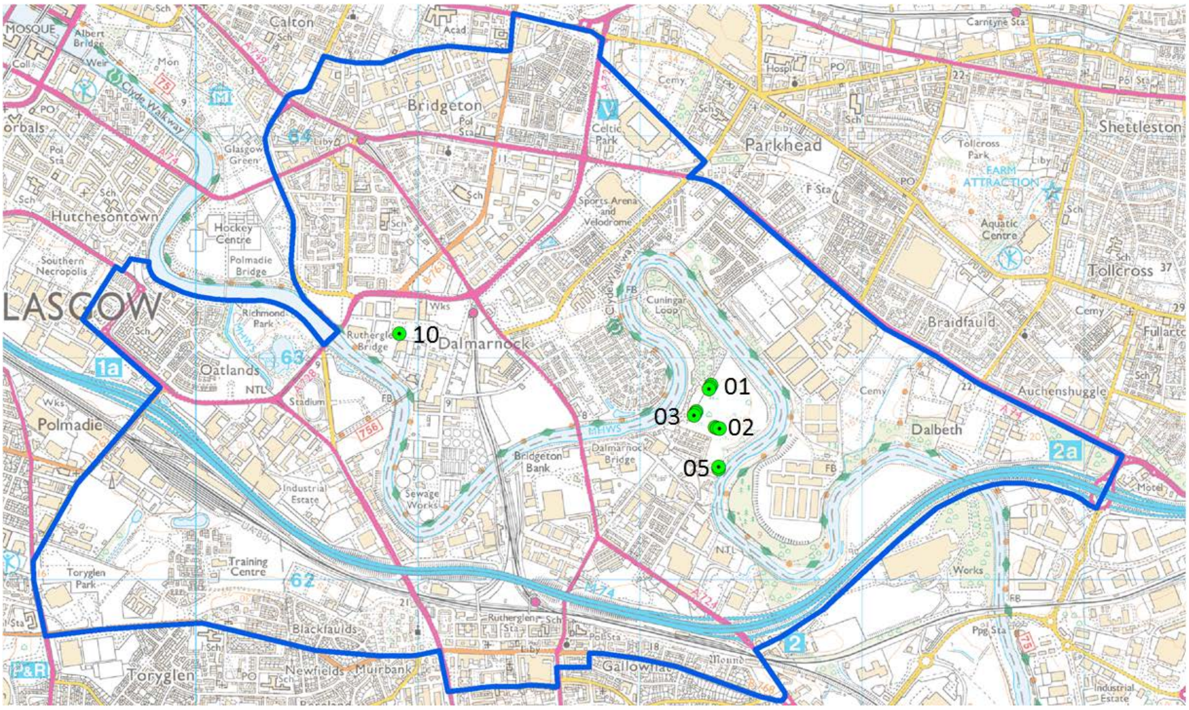

Figure 1. The Clyde Gateway regeneration area (blue border) and proposed borehole location sites with the location number (green points). Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2019. Licence number 100021290

2.1 TARGET FORMATIONS

The Scottish Middle and Lower Coal Measures formations have been extensively mined in the area and these partially open or collapsed mines are the target formations for low temperature geothermal energy and thermal storage.

3 Geotechnical data and its distribution

This report synthesises legacy data held in the BGS National Geotechnical Properties Database from previous site investigations, prior to the drilling of the UK Geoenergy Observatories (UKGEOS) boreholes.

The geotechnical data presented in this report comes from civil engineering projects and is provided by clients, consultant and contractors. Data is added to the British Geological Survey's National Geotechnical Properties Database (for information on the database see Self et al. 2012) from analogue (paper and pdf reports) and Association of Geotechnical and Geoenvironmental Specialists (AGS) data transfer format files. Most of the data was added for the work associated with the production of the Geotechnical GIS of central Glasgow (quarter sheets NS56SE, NS56NE, NS66SW and NS66NW) with recent additions of data donated (AGS) data transfer format files. The data density not only depends on the number of boreholes but also the depth of the boreholes, which controls the lithostratigraphical units intersected and number of sample points down the borehole. Also, the thickness of the superficial thickness, as shown with the borehole terminal depths, can be used to identify which boreholes are likely to intercept the bedrock (Figure 2).

The location of the standard penetration test data (Figure 3) and water content, plasticity and density (Figure 4) are mostly from the Clyde Gateway regeneration area. Particle size data is mostly from the Clyde Gateway regeneration area but also to the south (Figure 5). Rock uniaxial compressive strength data (Figure 6) is from the same area but few most of the data are out with the regeneration area. The rock quality designation (Figure 7) and fracture index (Figure 8) are from a wider area.

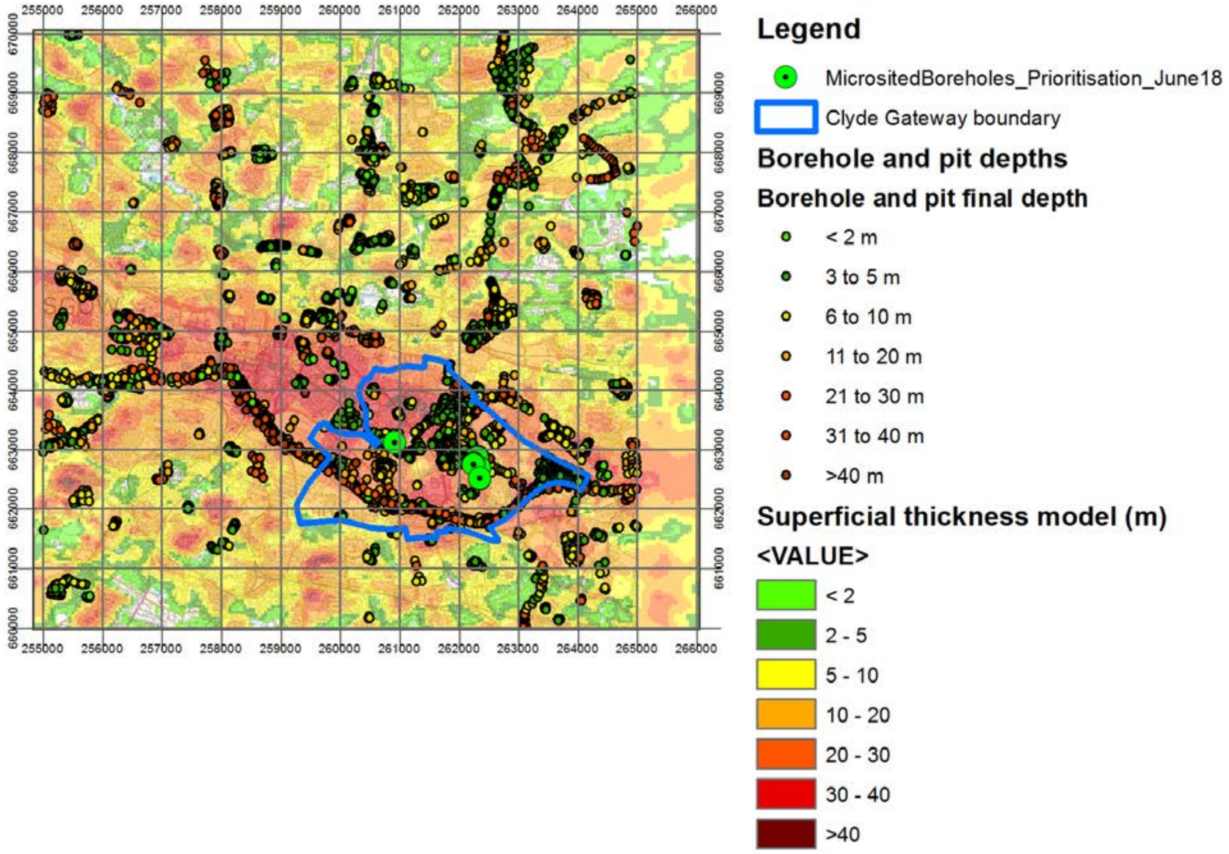

Figure 2. Location of the site locations, Clyde Gateway boundary, final depth of boreholes and pits from the BGS National Geotechnical properties Database and the superficial thickness model. **(Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2019. Licence number 100021290 EUL)**

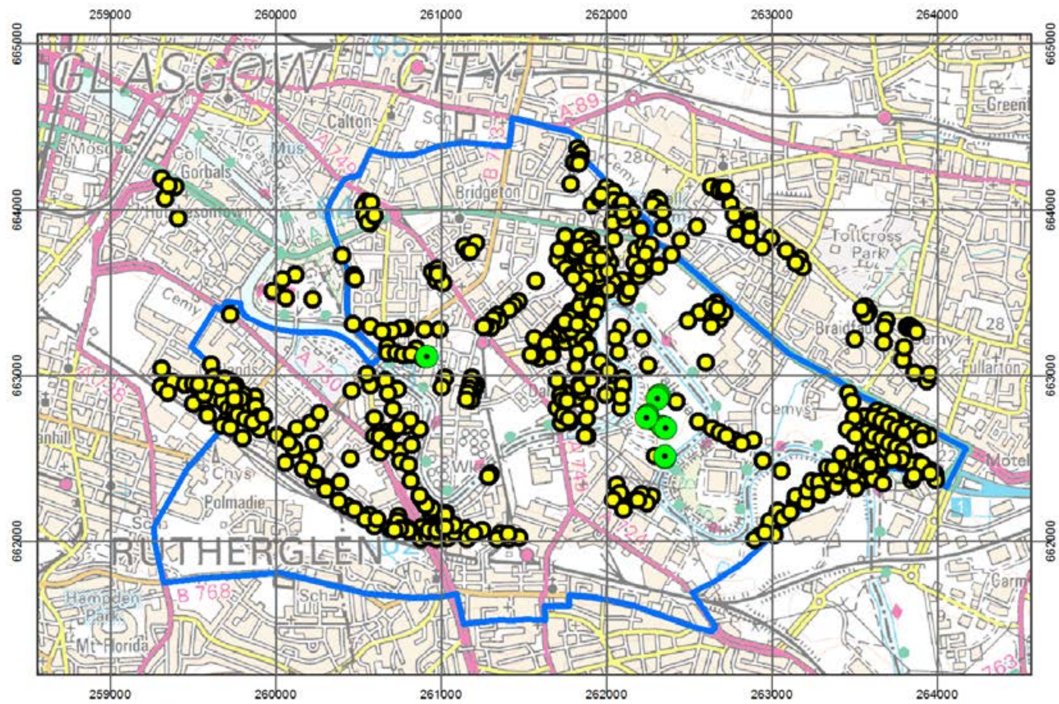

Figure 3. Location of boreholes in which standard penetration test data (yellow points) and proposed borehole location sites (green points). The Clyde Gateway regeneration area (blue border). (Includes mapping data licensed from Ordnance Survey. © Crown Copyright).

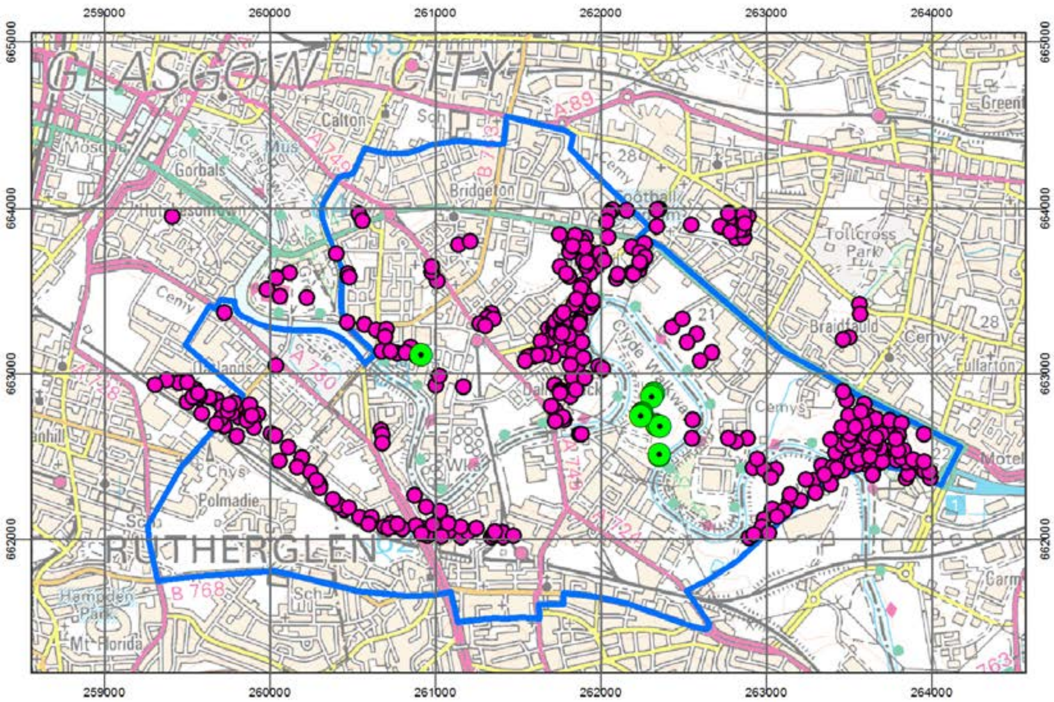

Figure 4. Location of water content, plasticity limit and density data (pinkish purple points) and proposed borehole location sites (green points). The Clyde Gateway regeneration area (blue border). (Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2019. Licence number 100021290 EUL).

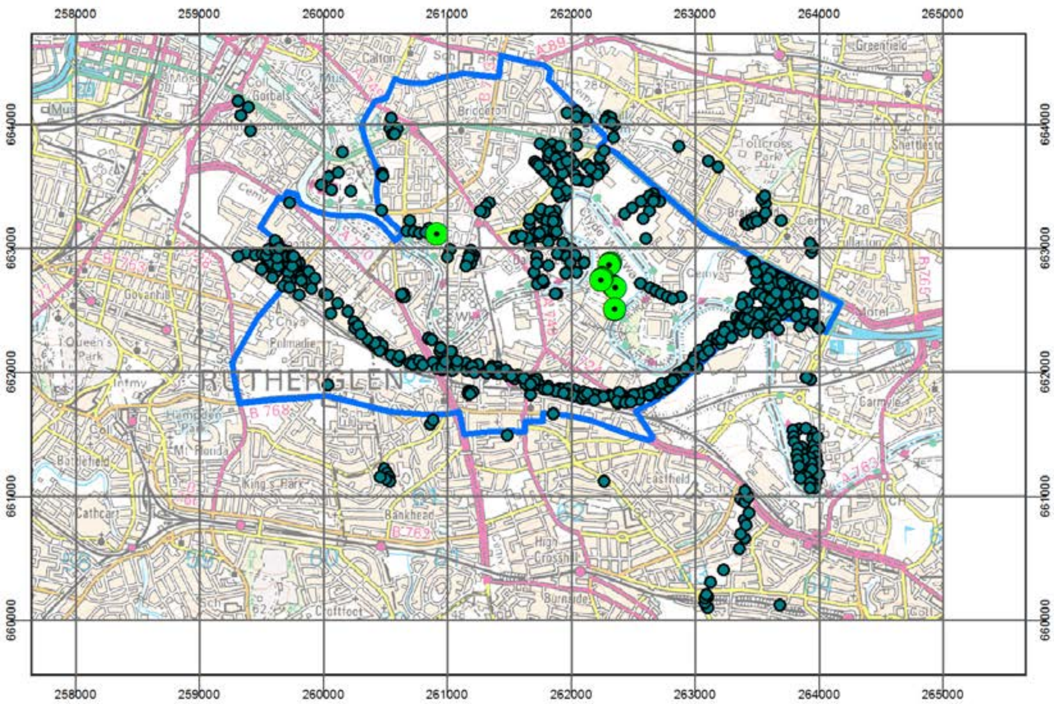

Figure 5. Location of particle size data (dark blue) and proposed borehole location sites (green points). The Clyde Gateway regeneration area (blue border). (Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2019. Licence number 100021290 EUL)

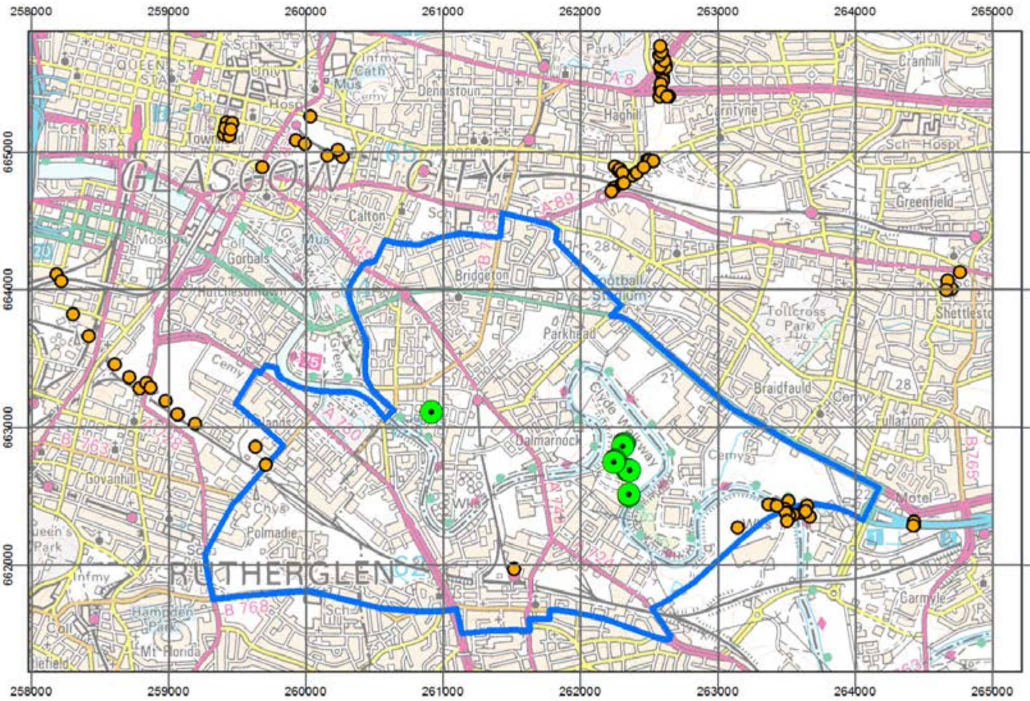

Figure 6. Location of rock uniaxial compressive strength data (orange points) and proposed borehole location sites (green points). The Clyde Gateway regeneration area (blue border). **(Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or d database right 2019. Licence number 100021290 EUL).**

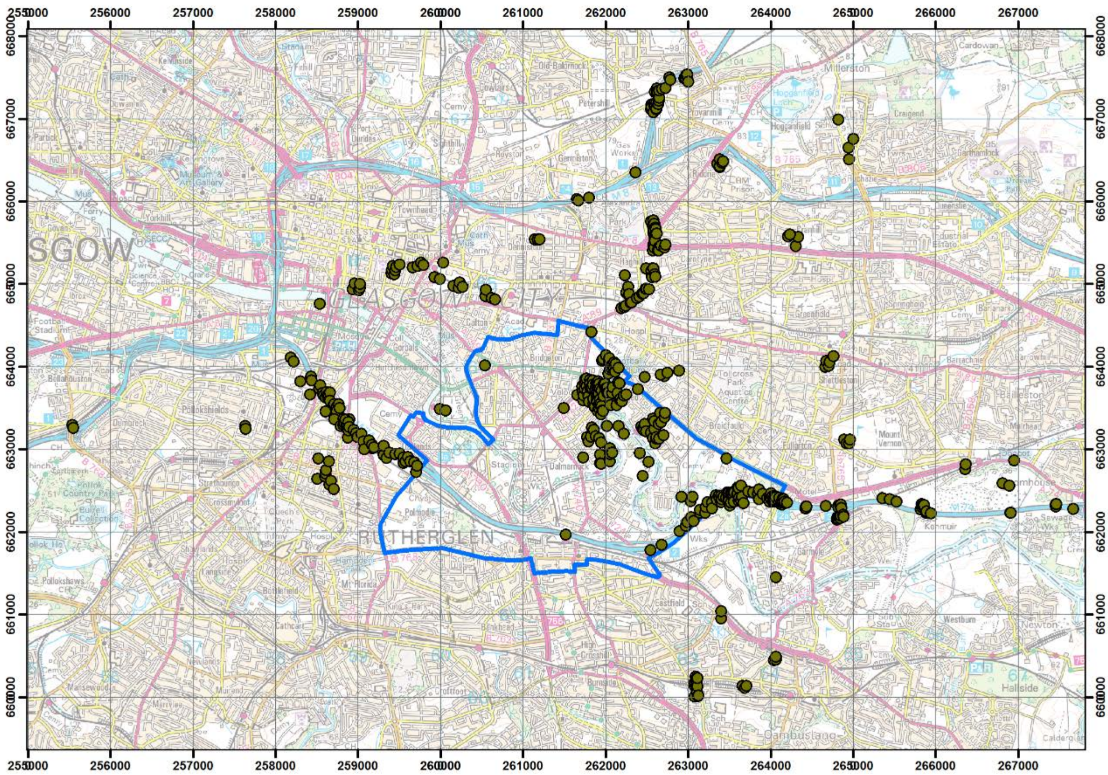

Figure 7. Distribution of rock quality designation data (dark green points) and proposed borehole location sites (green points). The Clyde Gateway regeneration area (blue border). **(Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2019. Licence number 100021290 EUL).**

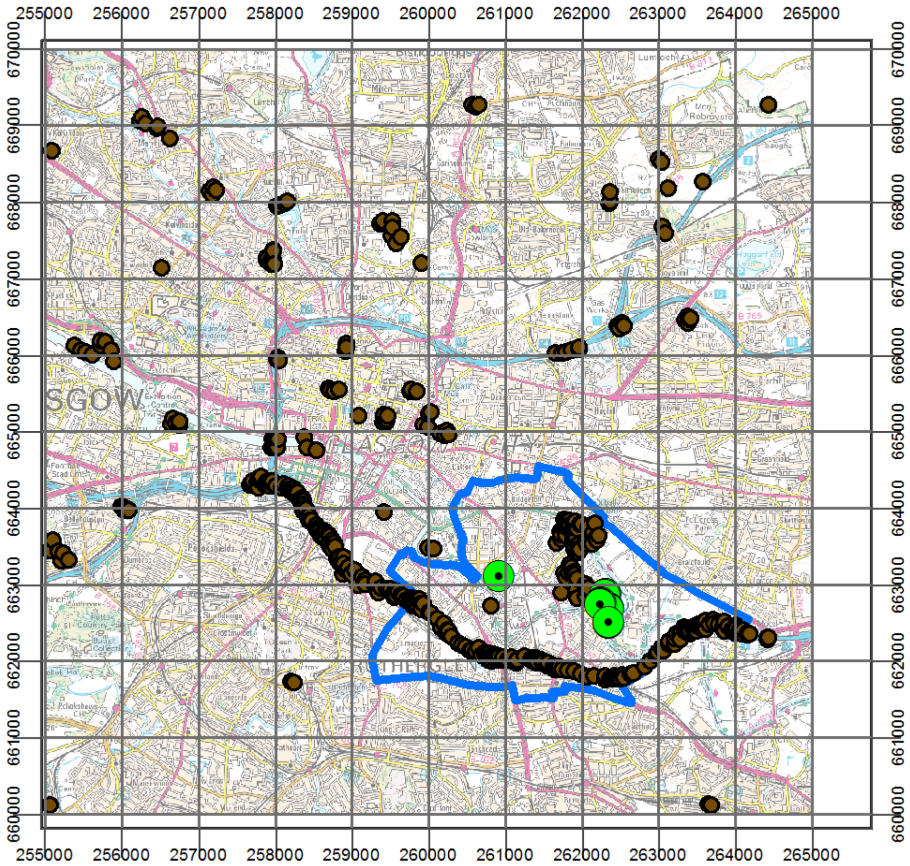

Figure 8. Distribution of fracture index data (brown points) and proposed borehole location sites (green points). The Clyde Gateway regeneration area (blue border). (Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2019. Licence number 100021290 EUL).

4 Engineering Geology

Superficial (including anthropogenic deposits) and bedrock units will be intersected by the UKGEOS boreholes, as identified by the 3D geological model superficial units (Arkley, 2018) and bedrock units (Kearsey and Burkin, 2018). The superficial units in order are:

- Made Ground (anthropogenic deposits)
- Gourock Sand Member
- Paisley Clay Member and
- Wilderness Till Formation

The bedrock units are in order:

- Scottish Middle Coal Measures Formation;
- Scottish Lower Coal Measures Formation.

The current geological map of the area (BGS, 2007) indicates that Location 10 is underlain by the Scottish Upper Coal Measures Formation, close to its subcrop. However, recent bedrock modelling (Kearsey and Burkin 2018) indicates that this unit is not present in this location and so it is not included in the borehole prognosis. The Midland Valley Carboniferous to Early Permian Alkaline Basic Sills Suite occur in the wider Clyde Gateway area cutting older stratigraphic units and whilst not included in the borehole prognoses, this unit is included in this report as it might occur.

The superficial geological units included in this report are listed with their depositional origin in Table 1.

Table 1. Superficial deposits units.

Lithostratigraphical unit and code	Age	Depositional environment
Anthropogenic deposits (MGR)	From mid-19th century to current day	Ground altered by man possibly including made ground, fill, infilled ground etc.
Gourock Sand Member (GOSA)	Holocene	Estuarine and fluvial.
Paisley Clay Member (PAIS)	Early Windermere Interstadial-Loch Lomond Stadial (MIS2-1) (Browne and McMillan 1989)	Raised marine clay and silt deposits.
Bridgeton Sand Member (BRON)	Latest main late Devensian Stade to earliest Windermere Interstadial. (McMillan et al. 2010)	Raised marine outwash deposits.
Broomhouse Sand and Gravel Formation (BHSE)	Dilmington Stadial to Windermere Interstadial. (McMillan et al. 2010)	Glaciofluvial (for the unit in this area).
Wilderness Till Formation (WITI)	Late Devensian: Dilmington Stadial (McMillan et al. 2010)	Primarily sub glacial (glaciotectonic) unit with minor glaciofluvial and glaciolacustrine beds.

When investigating the engineering properties it is important to understand the depth range of the units under consideration so that the engineering properties information is relevant to that depth. The geological history also needs to be considered, such as Quaternary erosional surfaces, past and recent weathering. To this end, Table 2 contains the approximate depths of the bases of each unit for each borehole location derived from the UKGEOS 3D geological model of the area (Arkley 2018; Kearsey & Burkin 2018) and summarised in borehole prognosis logs. A brief lithological description of the geological units are in Table 3.

Table 2. Superficial and bedrock unit base prognoses below surface at each site location to the nearest metre based on the UKGEOS 3D geological model (18/09/2018 prognosis logs).

Unit	Site location - modelled depth to unit base (m)				
	01	02	03	05	10
	GL +11 m OD	GL +11 m OD	GL +10 m OD	GL +12 m OD	GL +10 m OD
Anthropogenic deposits	12	11	3	7	1
Gourock Sand Member	15	14	11	17	6
Paisley Clay Member	21	24.7	22	24	24
Wilderness Till Formation	29	40	35	27	29
Scottish Middle Coal Measures Formation	>100*	>110*	>110*	>100*	180
Scottish Lower Coal Measures Formation	-	-	-	-	>220*

* Proposed borehole terminal depth.

Table 3. Summary description of superficial and bedrock units

Unit	Summary description
Anthropogenic deposits	Highly variable, depends on previous and current land use
Gourock Sand Member	Upper part – fine-grained with a local few organic beds or lenses Lower part – Sand, gravelly sand or sandy gravel
Paisley Clay Member	Clay and or silt often laminated with occasional gravel, local sand beds
Wilderness Till Formation	Gravelly sand clay with local low cobble and boulder count, local beds of commonly laminated clay or silt, local beds of sand, gravelly sand, sandy gravel or gravel sometimes with cobbles.
Scottish Middle Coal Measures Formation	Cyclical beds of mudstone, siltstone and sandstone with a few coal and seat earth beds with occasional local ironstone beds.
Scottish Lower Coal Measures Formation	Cyclical beds of mudstone, siltstone and sandstone with a few coal and seat earth beds with occasional local ironstone beds.

4.1 ANTHROPOGENIC DEPOSITS (MADE GROUND)

Glasgow has a long industrial and development history. The historical land uses in the Cuningar Loop, Locations 01, 02, 03 and 05, are described in Ramboll 2018a and Location 10 (Ramboll 2018b) and summarised in Table 4.

Table 4. Main historical land use at the borehole locations (after Ramboll 2018a, 2018b)

Location 01, 02 and 03	Location 05	Location 10
Sand and gravel extraction	Close proximity to coal pit/colliery. Colliery and possible sand and gravel spoil heaps	Part of site print and dye works, bleaching ground more recently residential development (tenement) now clear ground

Anthropogenic deposits are often vertically and laterally highly variable. Their thickness and content depend on the previous land use, the geology and treatment of the land that produced the deposit. As can be seen from Table 2, at location sites 01, 02, 03 and 05 these deposits are much thicker than at location 10. As anthropogenic materials are often highly variable and so the descriptions should be considered to be local to the borehole unless shown otherwise (for instance a common land use history) and should be only be considered to be a guide for the Location sites.

4.1.1 Location 01

The closest two boreholes to Location 01 are deeper boreholes down to 51 m below ground level. The closest, NS66SW573 from about 20 m north of the location, and NS66SW1785/M2 is about 40 m north of the location were drilled in 1979 before the modern standardisation of lithological description . Also, the upper part of the boreholes, down to a depth of 27.5 m, were drilled using open hole methods and so the descriptions are very limited, and their lithostratigraphical interpretation is not always straight forward. The upper 9.4 m are described as ‘forced material’ and a further over 3 m as “loose clay stones (probably forced)”. Other borehole and pit described below are from more than 50 m from the location.

Table 5. Anthropogenic deposits near borehole Location 01

Borehole	Grid reference	Depth (m) base	Description
NS66SW17585/PE about 64 m west	262250, 662880	0.95	Layers of brown SAND/CLAY with ash and brick and broken glass, bottles, polythene (strong odour – bleach?) – FILL MATERIAL
		2.90	General rubble – slates, brick, wire, masonry block, piece of carpet, all in brown sand matrix (FILL MATERIAL)
		3.10	Dark grey ASH with pieces of wood and brick – FILL MATERIAL (Base of pit)
NS66SW17585/C3 About 108 m SE	262410, 906620	4.6	Medium dense brown to dark brown SAND with ash, brick fragments, gravel, tabular wood pieces etc., some clayey zones (FILL MATERIAL)
		8.75	Very loose dark ash and SAND with slate, tabular wood, glass and brick fragments, gravel, clayey zones etc. (FILL MATERIAL)
NS66SW2459 about 107 m ESE	262419, 662840	0.1	TOPSOIL
		8.0	MADE GROUND (brown clayey gravelly fine to coarse sand with brick and concrete fragments)

4.1.2 Location 02

As with Location 01, the nearest borehole to Location 02, borehole NS66SW17585/M6, which is about 40 m west, is a deeper borehole down to 51 m below ground level, but the top 25 m were drilled by a Pilcon rig and there is no lithological log for this part of the borehole. Those nearby boreholes and pits that contain description are in Table 6.

Table 6. Anthropogenic deposits near borehole location 02

Borehole	Grid reference	Depth (m) base	Description
NS66SW4909/10 about 65 m SSE	262365, 662620	7.5	Loose grey ash (probably sand and gravel)
NS66SW2460 about 70 m west	262276, 662727	0.3	Topsoil
		0.7	Dark brown sandy gravelly CLAY with traces of glass and burnt shale
		3.3	Dark brown slightly clayey gravelly SAND with some wood and cobble size fragments of brick, sandstone and concrete.
		8.0	Dark brown and black clayey very gravelly SAND with much ash and occasional glass, pottery, plastic and slag with thin pale yellow clay at top
NB66SW17585/PC About 77 m NE	262410, 662730	3.00	General rubble – masonry blocks, bricks, wooden planks, bedstead, polythene bags, boulders, reinforced concrete slab (1 m x 1 m), wire, some burnt wood, part brick walls, lenses of clay, all in a matrix of

			dark (becoming greyish at 1.6 m – ashy) sand – FILL MATERIAL
		4.2	Black to dark grey sand size ASH with gravel to cobble size fragments, shiny fragments and tarry lenses – FILL MATERIAL (End of pit)

4.1.3 Location 03

The descriptions of Anthropogenic deposits in boreholes and pits nearby Location 03 are in Table 7. Borehole (NS66SW2460), 30 m to the east, is described in Table 6. Borehole NS66SW591, about 55 m north west of the location, does not include any description of Anthropogenic deposits.

Table 7. Anthropogenic deposits in a borehole near location 03

Borehole	Grid reference	Depth (m) base	Description
NS66SW17585/PB about 60 m south west	262200, 662720	0.75	Brown SAND with bricks, bottles, wood, glass
		0.9	Light brown and dark grey fine SAND
		3.10	Blackish SAND (ash) with occasional gravel to cobble size fragments, bricks, plastic, jars, bottles, wooden planks, pipes and scent of sulfide
		4.15	Light grey SAND (ash), occasional gravel and cobble size. Loose light brown PEAT at 3.5 m. (Base of pit).
NS66SW4909/9 about 75 m south west	262195, 662695	4.00	Loose grey SAND (ash) and clay fill with gravel of brick, masonry and timber.
		4.70	Loose red grey burnt shale GRAVEL(?) and cobble(?) and silty SAND fill.
NS66SW17585/C5 about 60 m north west	262200, 662790	1.60	Blackish ash, some gravel and tabular wood fragments, general rubble – FILL MATERIAL (medium dense)
		3.10	LOOSE lightish brown very silty SAND – POSSIBLE FILL MATERIAL/DISTURBED GROUND
		5.60	LOOSE lightish brown very silty fine SAND with irregular zones of grey brown clayey silt, probable ash and brick fragments inclusions POSSIBLE FILL MATERIAL/DISTURBED GROUND -

4.1.4 Location 05

Table 8 contains descriptions from a borehole about 60 m west of the Location 05.

Table 8.The described anthropogenic deposits near Location 05

Borehole	Grid reference	Depth (m) base	Description
NS66SW2461 about 60 m west	262293, 662514	0.1	Topsoil
		6.5	Brown sandy gravelly CLAY with concrete,

			brick and ash
		9.5	Medium dense red brown very clayey SAND and gravel of ash and brick rubble.

4.1.5 Location 10.

Table 9 contains descriptions from boreholes and trial pits in the vicinity of Location 10. These indicate a metre or less of anthropogenic deposits, however, there is variable lithological content including natural and man-made material within about 30 m of the location.

Table 9. The described anthropogenic deposits near location 10

Borehole	Grid reference	Depth (m) base	Description
NS66SW3723 9 m south	260914, 663102	0.06	MADE GROUND (broken stone, hardcore
		0.25	MADE GROUND (brown sandy GRAVEL)
		0.32	MADE GROUND (yellowish brown fine to coarse SAND
		0.6	MADE GROUND - Greyish brown SAND and GRAVEL. Sand is fine to coarse, gravel is angular to sub-rounded firm to coarse predominantly of ash with traces of timber, brick debris and glass, occasional pockets of clay
NS66SW1449 22 m SSW	260916, 663099	<0.5	MADE GROUND: Reddish brown sandy fine to coarse angular GRAVEL comprising
		0.25	MADE GROUND: Medium dense grey silty fine to coarse SAND and fine to coarse angular GRAVEL of brick and mortar
		0.5	MADE GROUND: Loose dark grey with white flecks sandy fine to coarse angular GRAVEL. Boiler ash.
NS66SW3718 25 m ESE	260939, 663104	0.23	MADE GROUND: broken stone, hardcore, Geogrid at base
		0.40	MADE GROUND: Brown clayey sandy GRAVEL with medium to high cobble content, gravel is angular to sub-rounded fine to coarse of mixed lithologies including brick, debris, ceramics and plastic
NS66SW1424 20 m NNE	260920, 663130	0.1	MADE GROUND: Concrete slabs
		0.2	MADE GROUND: Yellow fine to coarse sand
		0.3	Dark brown sandy SILT with some fine to coarse angular gravel. Contains red mudstone, ash and glass
		0.45	MADE GROUND: Light brown silty fine and medium SAND with some angular gravel of mortar
		0.75	MADE GROUND: brown very silty, gravelly fine to coarse SAND. Gravel is fine to coarse angular to sub rounded. Contains brick, mortar and rotten timber
NS66SW3750	260884,	0.05	MADE GROUND: Broken stone, hardcore

31 m west	663117	0.7	MADE GROUND: Greyish brown slightly clayey very gravelly SAND, Gravel is angular to sub-rounded fine to coarse of mixed lithologies including mudstone, brick and ash.
		0.8	MADE GROUND: Greyish brown slightly sandy gravelly CLAY with pockets of organic clay and fragments of brick.
NS66SW3722 32 m west	260883, 663114	0.12	MADE GROUND: broken stone and hard core
		0.40	MADE GROUND: Brown sandy GRAVEL. Gravel is angular to sub-rounded fine to coarse of mixed lithologies including glass, ceramics, tar, brick and concrete, concrete blocks 0.6 x 0.6 x 0.6 m. Base is undulating.

The modelled thickness of the Anthropogenic Deposits are in Figure 9.

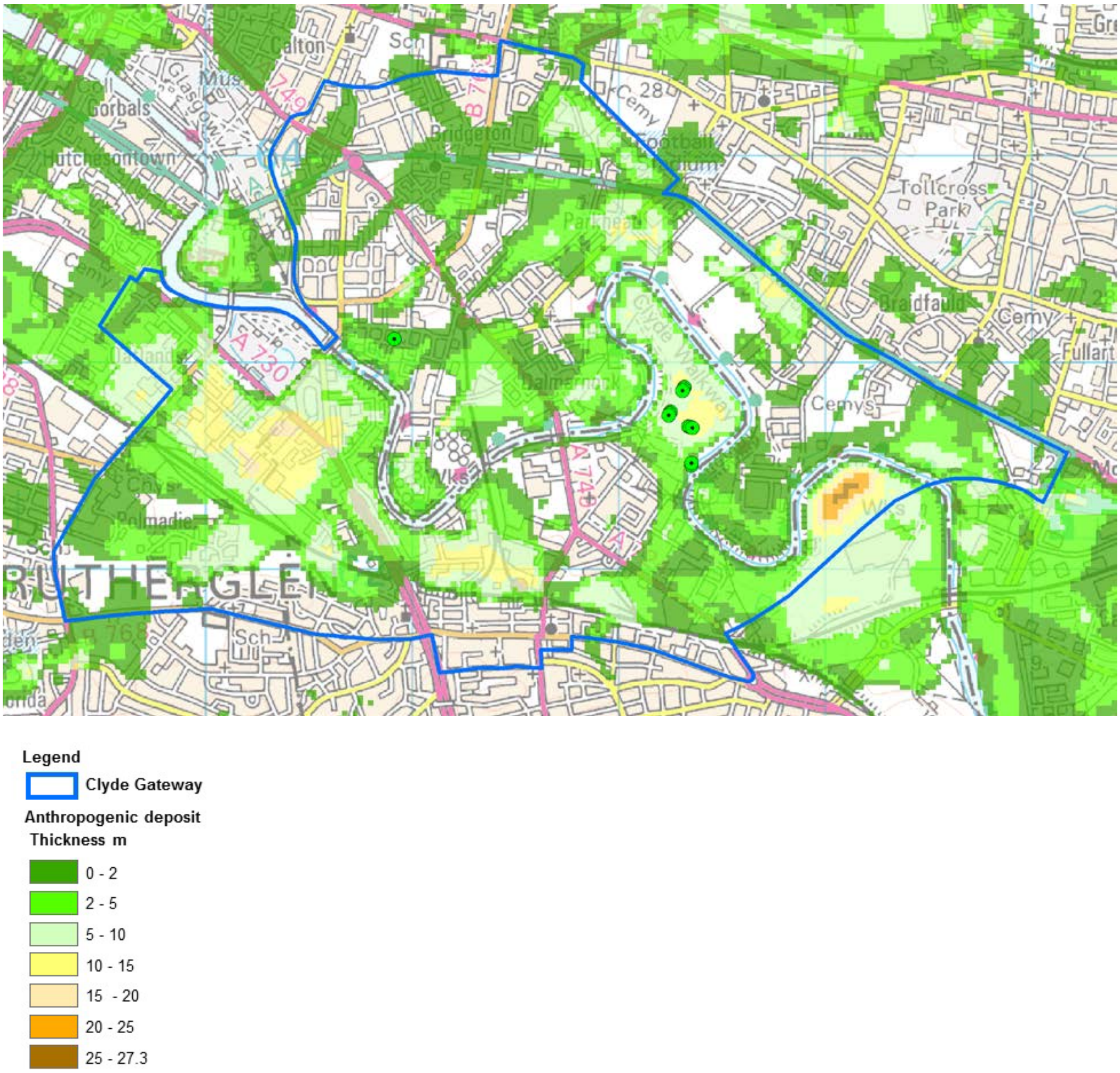

Figure 9. Modelled anthropogenic deposit thickness from the UKGEOS geological model (01/02/2019). (Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2019. Licence number 100021290 EUL)

4.1.6 Standard penetration test results

The ground investigation data in the area near proposed borehole locations 01 to 05 (Cuningar Loop) contains limited geotechnical data (only the borehole logs were available). The standard penetration test profile is in Figure 10. Most of the deposits are likely to be coarse-grained (from the limited borehole descriptions) and are, therefore, classified as mostly loose to medium dense. There is no apparent relationship between standard penetration test values and depth.

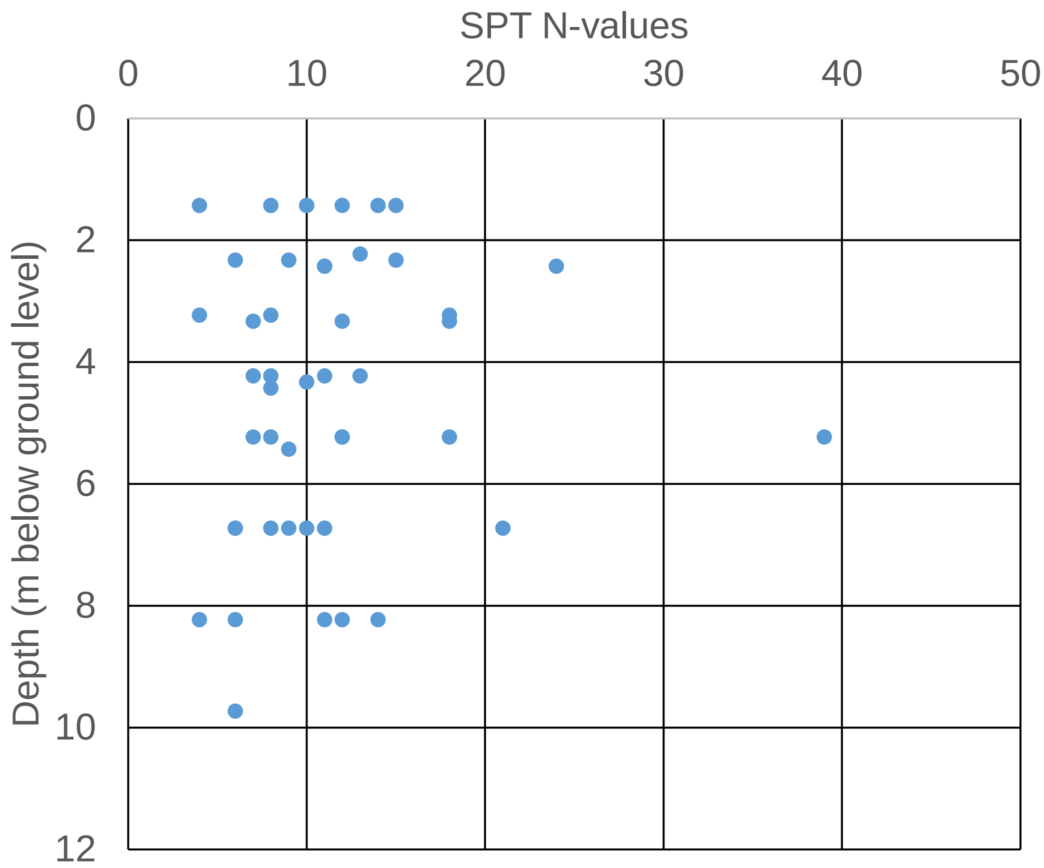

Figure 10. Standard penetration test values for anthropogenic deposits in the Cuningar Loop area (nearby boreholes near location 01, 02, 03, 05).

4.2 SUPERFICIAL DEPOSITS

4.2.1 Gourock Sand Member (GOSA)

4.2.1.1 INTRODUCTION

The Gourock Sand Member is an estuarine and fluvial deposit but in this area is primarily a fluvial deposit of Holocene age (Browne & McMillan 1989).

4.2.1.2 DESCRIPTION

The Gourock Sand Member of the Clydebank Clay Formation in this part of Glasgow typically contains a thin upper fine-grained upper part, sometimes with discontinuous beds or lenses of peat, on gravelly sand, sand or sandy gravel lower part, (Table 3) (Browne & McMillan 1989).

Location 01 borehole and pit descriptions

There are three borehole within 100 m of Location 01. Two of the boreholes, NS66SW579, NS66SW17585/M2 (see 4.1.1) do not describe lithologies of the Gourock Sand Member, and, therefore, are not included. The two borehole description, assumed to be Gourock Sand Member, are in Table 10 and from over 100 m from the location.

Table 10. Lithological descriptions of Gourock Sand Member in boreholes near Location 01

Borehole	Grid reference	Depth (m)	Description
NS66SW2459 about 107 m WSW	262419, 662840	Top 7.3 Base 15.00	Medium dense brown slightly clayey fine to medium SAND (base of borehole)
NS66SW17585/C3 About 108 m SE	262410, 662810	Top 8.75 Base 11.00	At top (depth not given) soft light brown sandy CLAY Light grey brown very silty micaceous SAND with fine black gravel, some clay lenses
		Base 16.00	Medium dense becoming loose brown medium to coarse SAND and mixed generally sub-rounded gravel and cobbles

Location 02 boreholes descriptions (Table 11).

Table 11. Lithological descriptions of Gourock Sand Member in boreholes near Location 02

Borehole	Grid reference	Depth (m)	Description
NS66SW4909/10 about 98 m SW	262365, 662620	Top 7.5 Base 9.8	Medium dense light brown and brown fine to medium SAND and occasional gravel.
		Base 12.7	Medium dense light brown coarse SAND and abundant rounded gravel and cobbles.
NS66SW2468 About 108 m E	262447, 662680	Top 11.00 Base 16.5	SAND and GRAVEL

Location 03 boreholes descriptions (Table 12)

Table 12. Lithological descriptions of Gourock Sand Member in boreholes near Location 03

Borehole	Grid reference	Depth (m)	Description
NS66SW2460 about 38 m ESE	262276, 662727	Top 8.0 Base 8.6	Soft and firm greyish brown sandy and very sandy CLAY with occasional lenses of brown fine and medium sand.
		Base 10.0	Medium dense greyish brown slightly silty slightly gravelly fine and medium SAND
		15.00	Medium dense brown medium and coarse SAND and sub-angular and sub-rounded fine to coarse GRAVEL Base of borehole
NS66SW17585/C5 About 62 m NW	262200, 662790	Top 5.6 Base 6.6	Loose brown silty fine SAND very occasional gravel

		Base 9.0	Medium dense brown medium to coarse SAND and sub-rounded gravel and cobbles occasional silty zone
		Base 10.6	Medium dense brown medium to coarse SAND and sub-rounded gravel and cobbles, occasional silty zone with lenses of dark grey to black silty PEAT
		Base 11.5	Medium dense brown medium to coarse SAND and sub-rounded gravel and cobbles, occasional silty zone
NS66SW4909/9	262195, 662695	Top 4.7 Base 6.0	Mottled light and dark brown clayey and silty fine to medium SAND
		Base 7.5	Loose brown slightly silty fine and medium SAND and occasional gravel
		9.50	Medium dense light brown coarse sandy well rounded GRAVEL

Location 05 borehole descriptions are in Table 13.

Table 13. Lithological descriptions of Gourock Sand Member in boreholes near Location 05

Borehole	Grid reference	Depth (m)	Description
NS66SW2461 about 64 m W	262293, 662514	Top 9.5 Base 11.0	Medium dense brown slightly silty brown fine to medium SAND and occasional gravel.
		Base 15.0	Medium dense brown fine to coarse SAND and sub-rounded and rounded fine to coarse gravel Base of borehole.
NS66SW17585/SG1 About 62 m WSW	262290, 662490	Top 5.7 Base 7.4	Soft light reddish brown (to grey in parts) micaceous very silty sandy CLAY, Possible disturbed
		9.9	Soft to firm dark grey brown laminated silty CLAY with partings of sand and/or silt, some light brown
		14.3	Loose generally light brown medium to coarse SAND and mixed sub-angular to sub-rounded GRAVEL

In the Cuningar Loop area around locations 01, 02, 03, 05, the fine-grained upper bed of the Gourock Sand Member is missing from many of the boreholes or pits below the Anthropogenic deposits. It is present in some of the boreholes in the south of the area and also across the River Clyde (for instance NS66SW2988/19 [262060, 662990]). It is likely that much of the fine-grained material has been removed or intermixed with other materials because of human activity (see 4.1).

Location 10 borehole and pit descriptions

The western location in Dalmarnock at borehole Location 10 contains both the upper and lower parts of the Gourock Sand Member. Descriptions from boreholes in the vicinity of location 10 are in Table 14.

Table 14. Lithological descriptions of Gourock Sand Member in boreholes near Location 10

Borehole	Grid reference	Depth (m)	Description
NS66SW3723 about 10 m south	260914, 663102	Top 0.6 Base 1.85	Firm light grey mottled orange sand CLAY
		Base 3.15	Light orangish brown slightly gravelly silty fine to coarse SAND with medium cobbles content. Gravel is angular to sub-rounded of mixed lithologies. Cobbles are rounded predominantly of quartzite. Base of pit
NS66SW1438 About 37 m WSW	260880, 663100	Top 0.5 Base 1.2	Firm greyish brown thinly laminated silty CLAY with occasional lenses of mottled light brown and grey sandy CLAY
		Base 6.1	Loose brown medium to coarse SAND with some locally much fine to coarse sub-rounded gravel
NS66SW3750 about 37 m west	260884, 663117	Top 0.8 Base 1.85	Light greyish brown orange (silty) CLAY
		Base 2.8	Light greyish mottled orange slightly gravelly silty SAND. Gravel is sub-angular to rounded fine to coarse of mixed lithologies
		Base 5.0	Light brown slightly clayey fine to coarse SAND and angular to sub-rounded fine to coarse GRAVEL of mixed lithologies
NS66SW3687 About 40 m north	260906, 663151	Top 0.8 Base 1.85	Light greyish brown mottled orange silty CLAY
		Base 2.8	Light greyish brown orange slightly gravelly SAND. Gravel is sub-angular to rounded fine to coarse of mixed lithologies
		Base 5.0	Light brown slightly clayey fine to coarse SAND and angular to sub-rounded fine to coarse GRAVEL of mixed lithologies
NS66SW1424 About 20 m north	260920, 663130	Top 1.2 Base 1.5	Firm becoming stiff light greyish brown mottled yellowish brown silty CLAY
		Base 1.8	Soft becoming soft to firm light yellowish brown mottled orange silty CLAY

		Base 3.0	Brown, silty fine to coarse SAND with occasional fine to coarse sub-angular to rounded gravel (Base of pit)
NS66SW3718 About 24 m ESE	260939, 663104	Top 0.4 Base 1.6	Firm light thinly laminated grey mottled orange sandy CLAY
		Top 1.6 Base 3.05	Light orangish brown gravelly fine to coarse SAND with medium becoming high cobble content. Gravel is angular to sub-rounded of mixed lithologies. Cobbles are sub-angular to rounded of mixed lithologies predominantly of quartzite. (Base of pit)

The percentage of principal soil lithology of this unit is shown along with other superficial deposit units in Figure 11 and shows that the Gourock Sand Member is principally coarse-grained, mostly sand, the middle and lower part, but with nearly 40% fine-grained, mostly in the upper part.

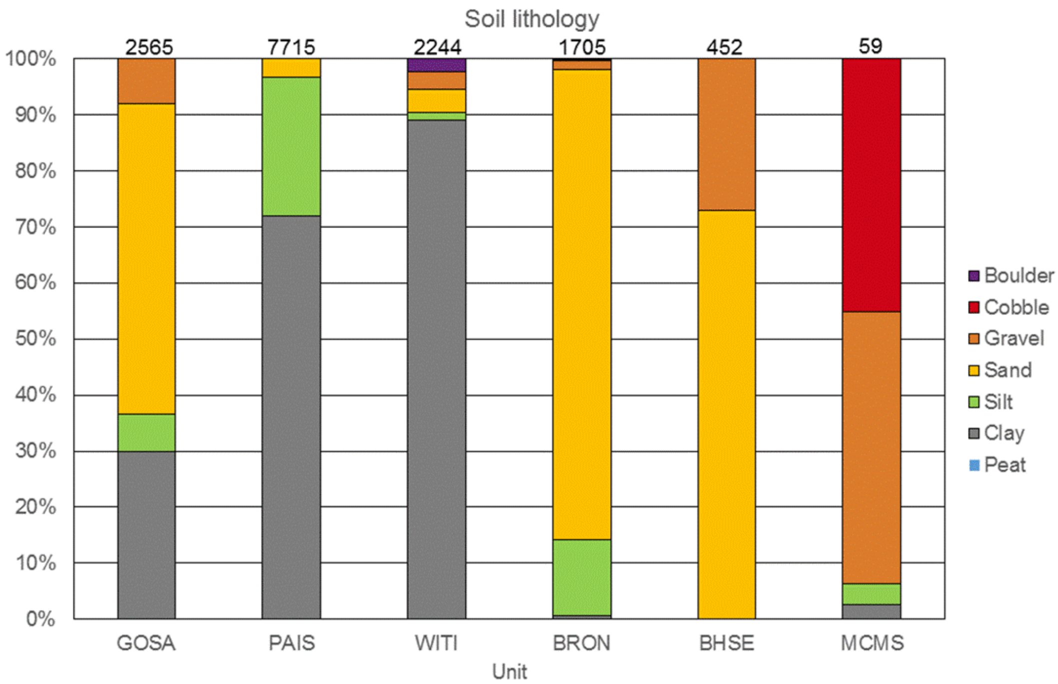

Figure 11. Percentage of described principal lithology of the superficial deposits and soil-like (residual soil) of bedrock (‘MCMS’ column) recorded in existing borehole data. Sample length in metres at top of each column.

4.2.1.3 Consistency

The fine-grained part of the Gourock Sand Member is mostly very soft to firm but is sometimes stiff (Figure 11).

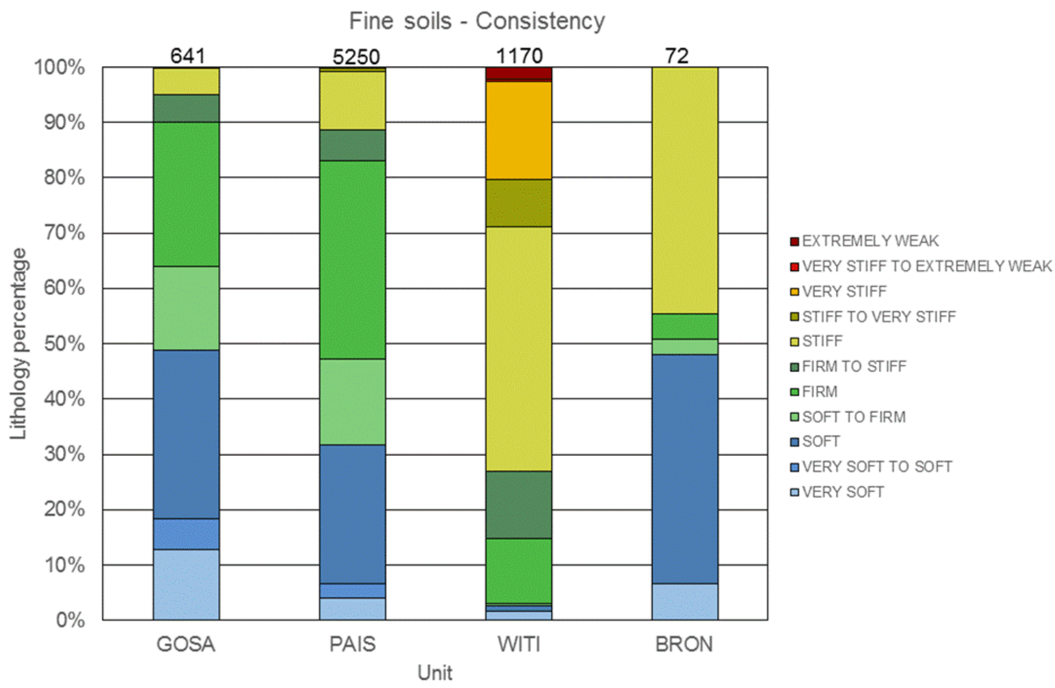

Figure 12. Described consistency of fine-grained soils from boreholes in the area as shown in Figure 4. Sample length in metres at top of each column.

4.2.1.4 Described density

The field relative density is classified for coarse-grained materials from the in situ standard penetration tests (SPT) N-values), carried out during cable percussion drilling using the classification in BSI (2015). The % of described density of the Gourock Sand Member is shown with other superficial units in Figure 13 and shows that most of this unit is loose to medium dense.

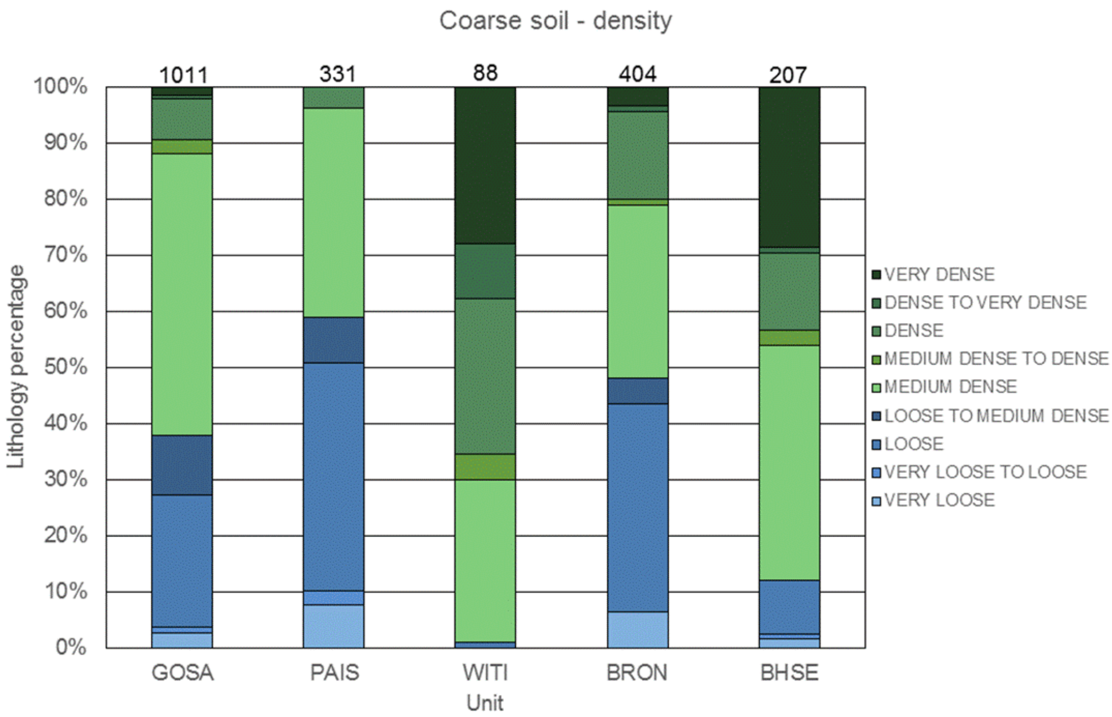

Figure 13. Density of coarse-grained soils recorded in ground investigation borehole data. Sample length in metres at top of each column.

4.2.1.5 STANDARD PENETRATION TEST

The data presented here is from the wider Clyde Gateway area (Figure 2).

Standard penetration test results are plotted against the mean test depth in Figure 14. It shows that both fine and coarse materials are present near the surface and that fine materials are present at depth. The distribution of the different lithologies is complicated by the possible removal of material and the deposition of Anthropogenic deposits above.

The fine-grained soils have generally lower values and are often described from hand tests as very soft to firm. The data for the coarse soils indicates that it varies between very loose (N-values <4 blows) to very dense (N-values >50 blows) but most are loose to medium dense (4 to 30 blows). There is a slight trend of increasing N-value with depth.

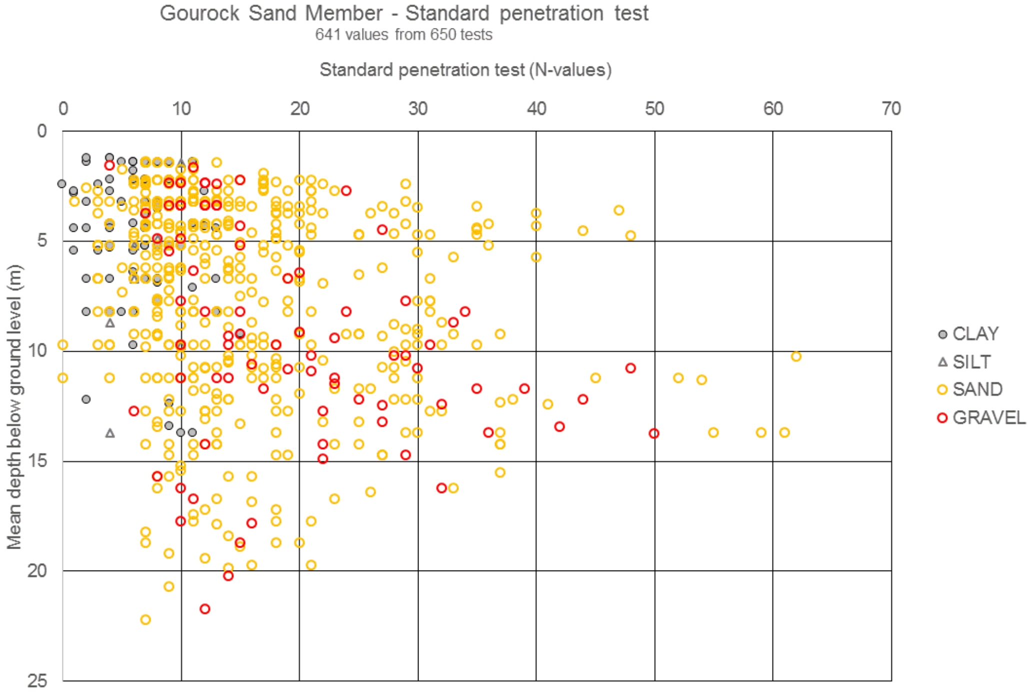

Figure 14. Gourock Sand Member - standard penetration test N-values against the mean depth of test differentiated for lithology.

Figure 15 shows the standard penetration test data plotted against the distance from the top of the unit. This is an attempt reduce the effects of the thickness of Anthropogenic deposits, which increase the depth of the test when compared to the natural situation. However, as it is likely that in some areas part of the Gourock Sand Member has been removed, for instance to north of the Cuningar Loop, the ‘top of the unit’ may not represent the natural top of unit.

This figure shows that most of the fine-grained material is within 4 m of the top of the unit, and that there is a trend of increasing N-values with depth, which is perhaps more marked in the gravel than in sand. However, the higher values do not appear to relate to depth.

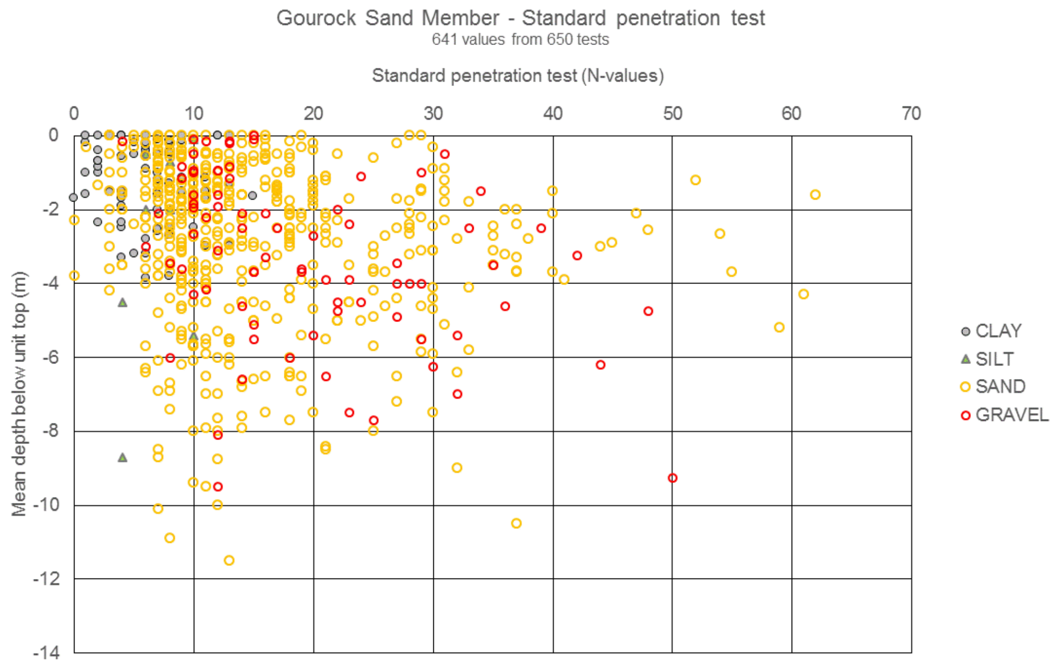

Figure 15. Gourock Sand Member - standard penetration test N-values against the distance from unit top of test differentiated for lithology.

4.2.1.6 WATER CONTENT

In Figure 16 the water content of the Gourock Sand Member has been plotted against distance from the top of the unit. The water content is, in part, dependent upon the lithology as it is difficult to retain water in coarse samples. For example, the measured water content of sand samples is unlikely to represent the in- situ content. Organic samples tend to have higher water content, then clay, gravelly clay, silt and sand. There is a greater variation near the top of the unit and this is probably due to differences in drying related to climatic factors and place in in the landscape. Also, there tends to be a reduction in water content with depth.

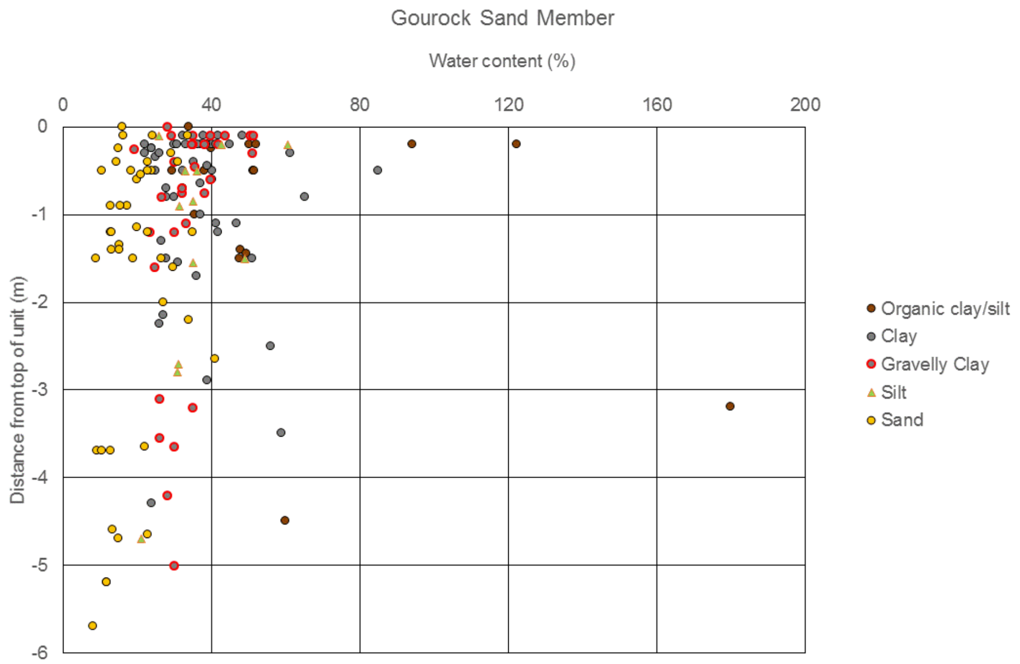

Figure 16. Gourock Sand Member water content plotted against distance from top of unit with lithology

4.2.1.7 Bulk and dry density

The bulk density and the dry density results are mostly for fine-grained soils as it is difficult to take undisturbed samples of coarse materials using standard sampling methods. The data is more applicable to the area near location 10, which has a more complete succession comprising both the fine-grained upper part and coarse-grained middle and lower part.

The bulk density (Figure 17) varies between 1.65 and 2.06 Mg/m^3 and the dry density between 0.44 and 1.72 Mg/m^3, with most of the data being greater than 1.04 Mg/m^3.

All the organic samples have bulk densities of less than 1.8 Mg/m^3 and the sample with the lowest value is described as a ‘firm to stiff slightly clayey peat’. Whereas, most of the other lithologies had values greater than 1.8 Mg/m^3. The clay, silt and sand bulk density values are similar with the greatest variation near surface. This might be due to the higher number of values and also to near surface processes including drying (producing higher values), or consolidation due to the loading of anthropogenic deposits.

The dry density values are plotted against distance from unit top in Figure 18. As with the bulk density, the organic fine-grained samples have lower dry density than the other lithologies, varying between 0.4 to 1.3 Mg/m^3 and a majority of the rest of the samples vary between 1.3 Mg/m^3 and about 1.73 Mg/m^3. Also, the greatest variability is in the top metre. Below about 2 m there is a trend for increasing dry density, however, there are few data points.

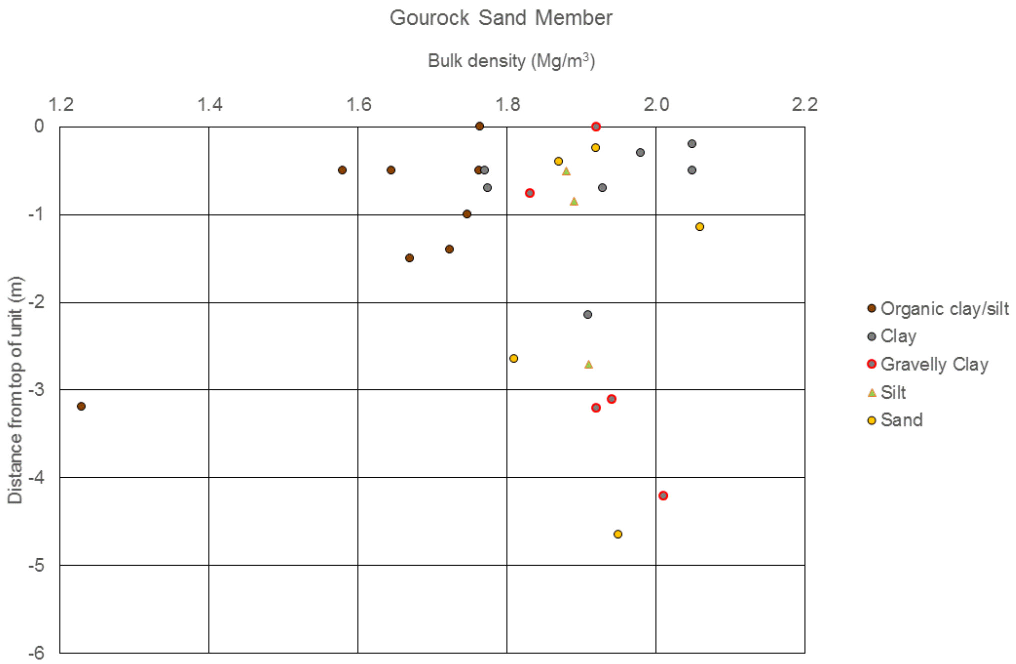

Figure 17. Gourock Sand Member bulk density vs distance from top of the unit with lithology

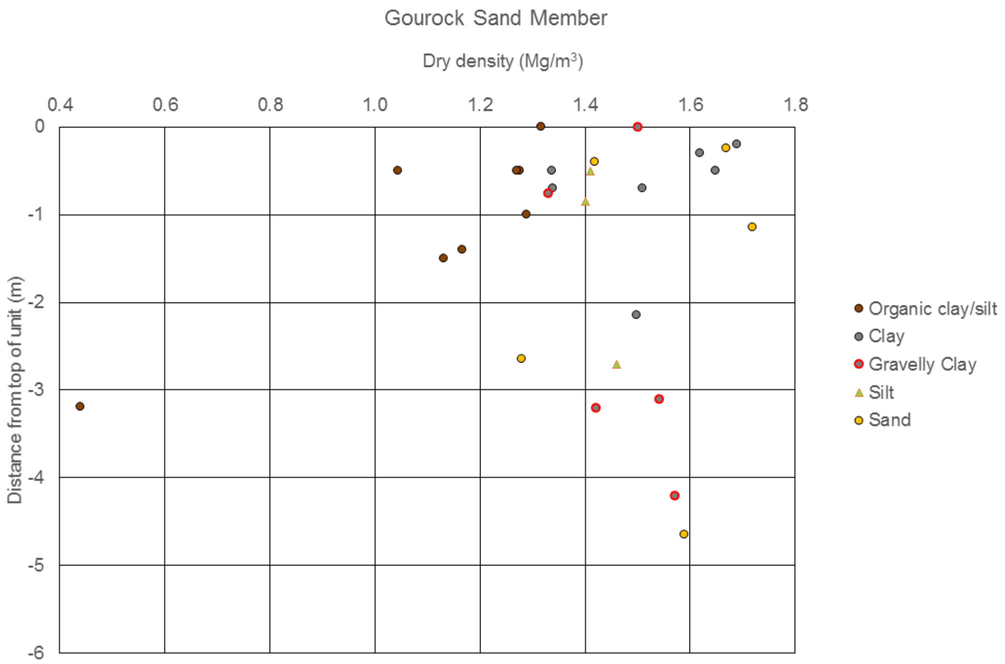

Figure 18. Gourock Sand Member dry density vs distance from top of unit with lithology

4.2.1.8 Particle size distribution

The particle size distribution graphs are separated into fine soils (mostly comprising samples described as “clay” or “silt”, these being predominantly from the upper part of the unit; Figure 19) and coarse soils (mostly present in the middle and lower part of the unit; Figure 20). The graph for fine soils shows each distribution, whereas the graph for coarse soils shows the data as percentiles as there is too much data to plot separate lines. Also, as much of the data does not contain particle size values for silt- and clay-size particles (<0.063mm), any values have not been included as they will bias the data as they are generally from samples with more finer grains. Figure 20 shows that the coarse part of the Gourock Sand member varies between a fine to coarse sand and a sandy fine to coarse gravel but is mostly a gravelly fine to coarse sand and sandy fine to coarse gravel.

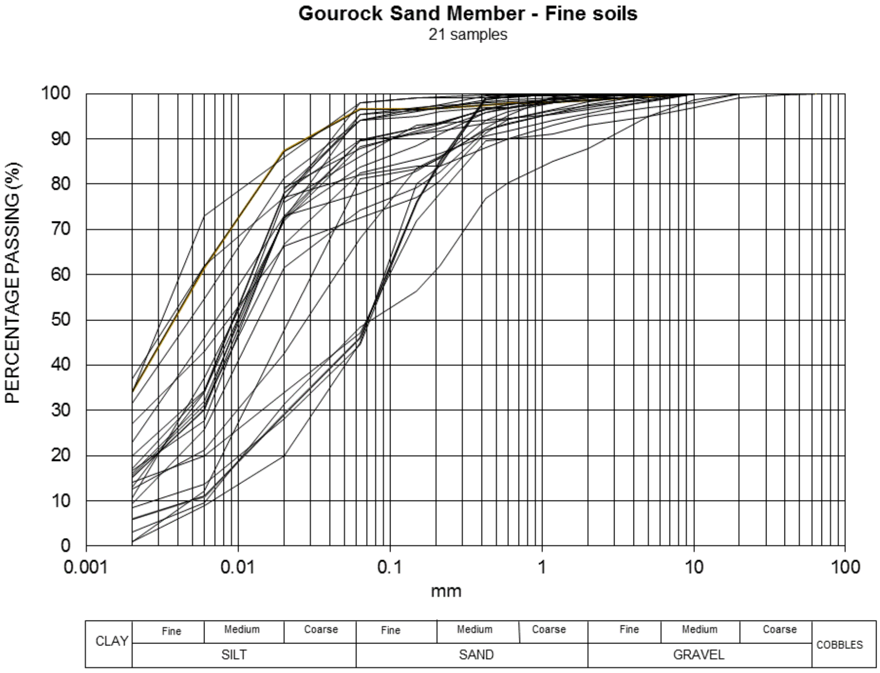

Figure 19. Gourock Sand Member fine soils particle size distribution

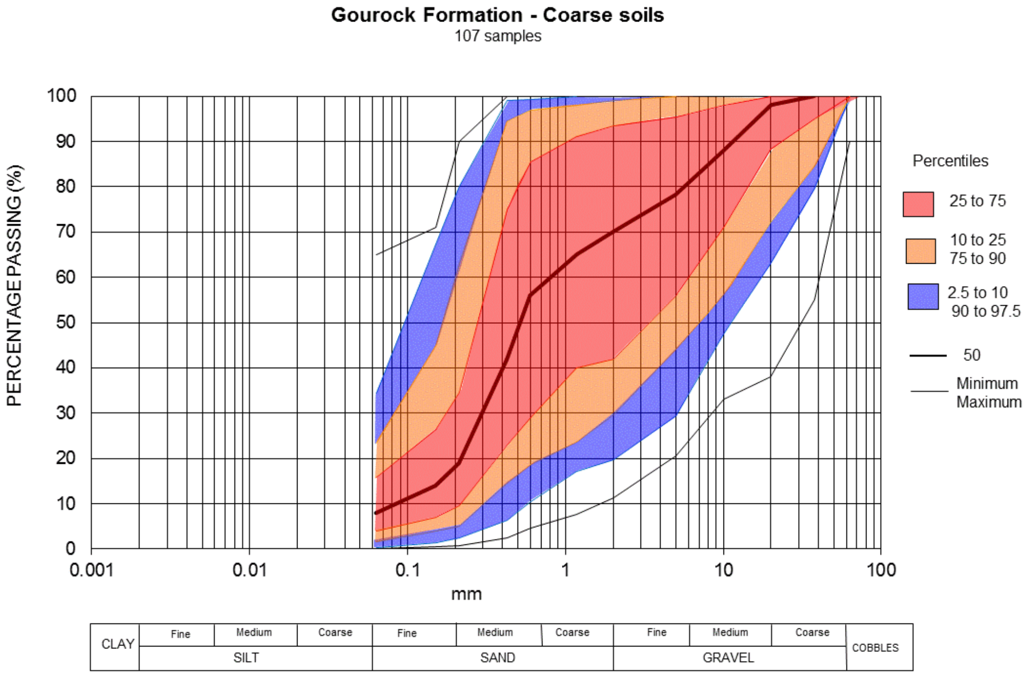

Figure 20. Gourock Sand Member particle size distribution coarse.

4.2.1.9 PLASTICITY

The Atterberg plasticity chart shows the relationship between the liquid limit and the plasticity index. Tests are carried out on <0.425 mm material and generally only for fine-grained soils. This graph provides a means of classifying the data as low to extremely high plasticity and as a clay (falling above the A-line) or a silt (below the A-line). Organic soils tend to have higher liquid limits than mineral soils and commonly lie below the A-line. Figure 21 shows the plasticity of the clay and silt of the Gourock Sand Member. The variability is likely to be due to clay and organic content. The extremely high plasticity values that lie on or below the A-line are mostly described as organic clays. This figure also shows that a number of samples described as silt plot above the A-line and some described as clay plot below the A-line. This might be due to the normal differences between the hand tests used to describe fine soils, inaccurate field description or the differences between the field and laboratory test approaches.

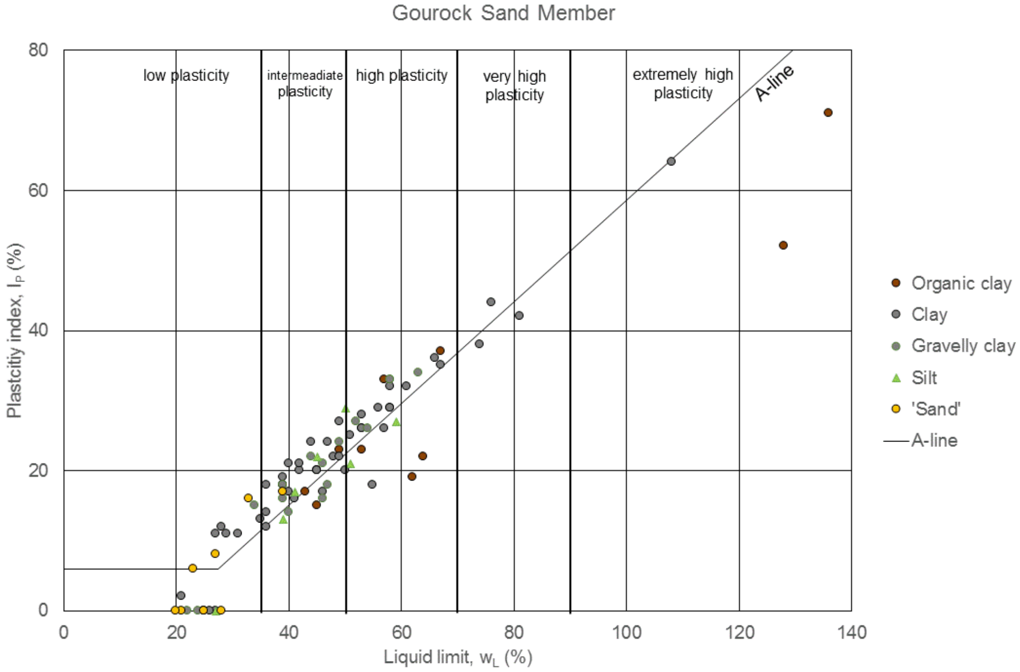

Figure 21. Plasticity chart for the Gourock Sand Member

4.2.1.10 CONSOLIDATION

As the drilling and possible subsequent surface infrastructure might be founded in the Gourock Sand Member, consolidation characteristics are included. The voids ratio plotted against the log stress (Figure 22) shows large difference reflecting the lithology of the different samples tested. The organic samples have higher voids ratios, as indicated by the water content (Figure 16) and dry density values (Figure 18).

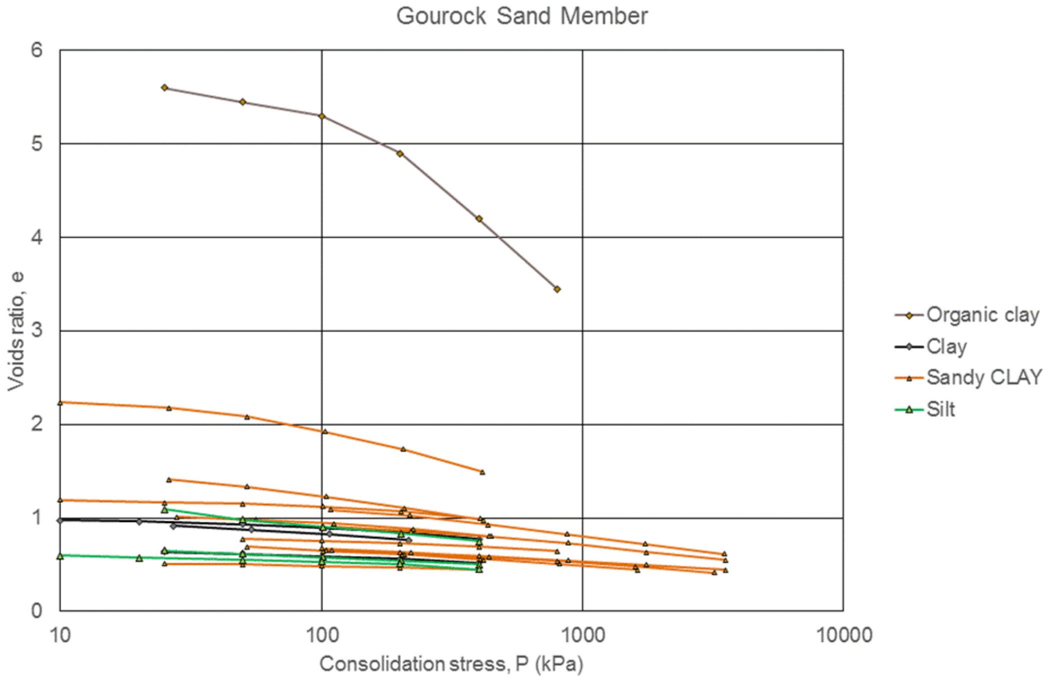

Figure 22. Gourock Sand Member consolidation data - voids ratio and consolidation stress.

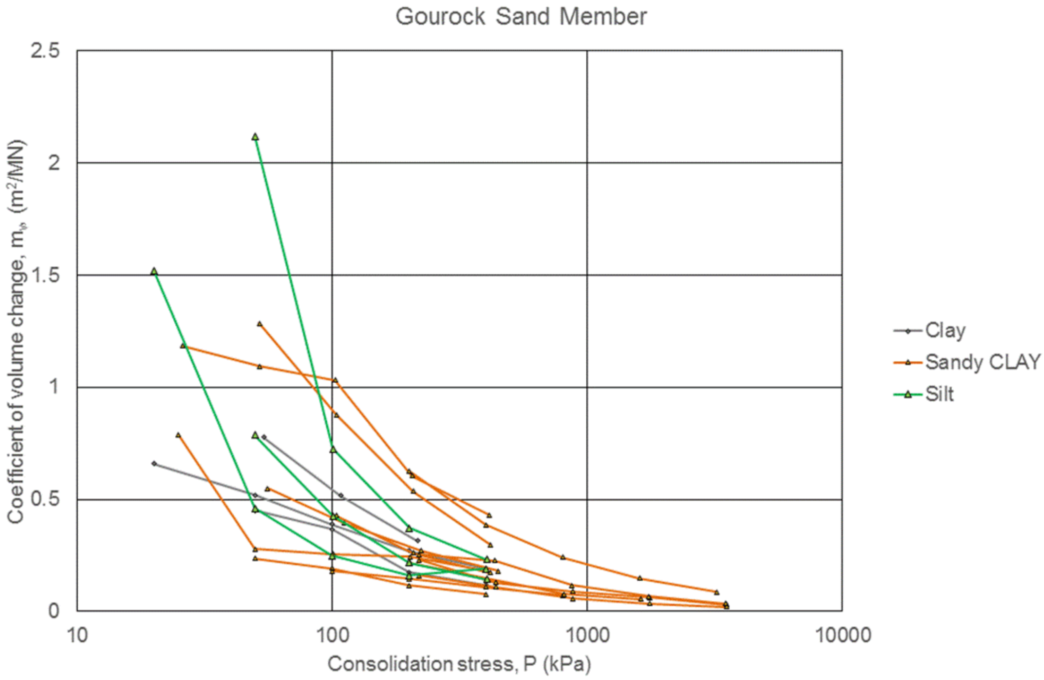

Figure 23. Gourock Sand Member consolidation - coefficient of volume change vs consolidation stress

The coefficient of volume change is a measure of the change in voids ratio with change in stress. The results are the inverse of the constrained modulus. Figure 23 shows a reduction in values with increasing stress, which is typical of alluvium and estuarine deposits. Also, the values at stresses of about 100 kPa and less are typical of alluvial and estuarine clays, i.e. between 0.3 and 1.5 m^2/MN.

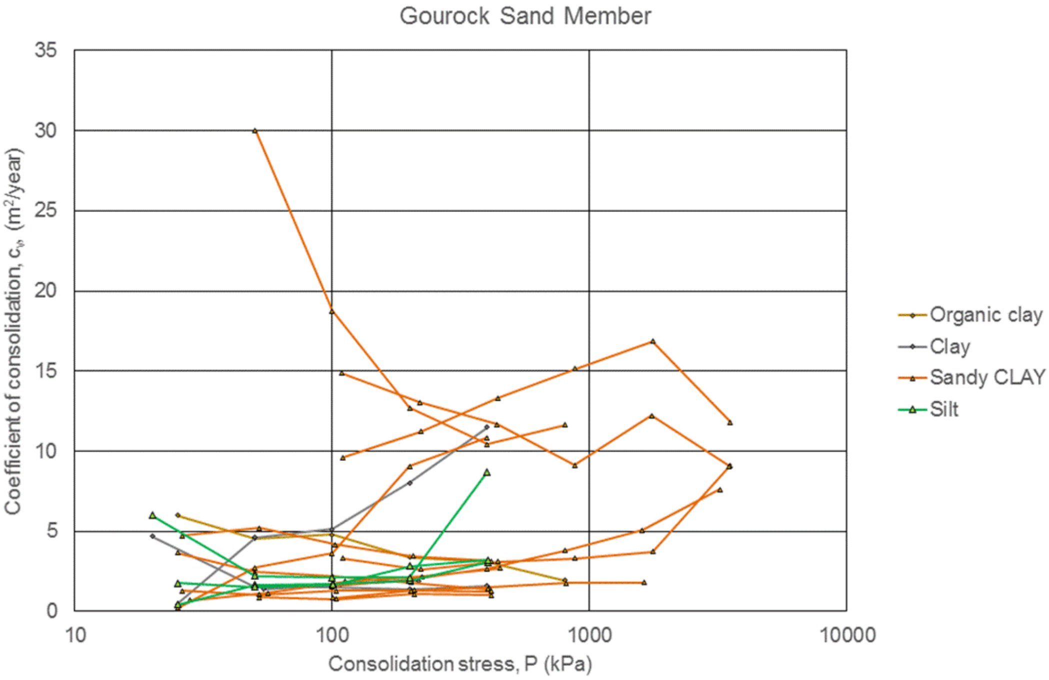

Figure 24. Gourock Sand Member consolidation - coefficient of volume change vs consolidation stress

The coefficient of consolidation, c_v, is a measure of the rate of consolidation: the higher the values, the more rapid the rate of consolidation. Figure 24 shows a wide range of rates for samples that are described as having similar lithology. Surprisingly, those samples that are described as silt have lower values than some of the sandy clay samples.

4.2.2 Paisley Clay Member (PAIS)

4.2.2.1 Introduction

The Paisley Clay Member is a raised marine clay or silt, locally sand, deposited during the early Windermere interstadial.

4.2.2.2 Description

The Paisley Clay Member is mostly soft to firm, but occasionally very soft or stiff, often laminated, grey, brownish-grey or brown clay sometimes with thin layers or partings of silt, or silt with partings of clay. Locally, as in the Clyde Gateway area, it can be a sandy clay or silt containing beds of loose to medium dense grey, brownish grey or brown clayey or silty mostly fine to medium sand, sometimes with thinly laminated silt or clay.

The principal described lithology (Figure 11) is clay over 70%, silt 27% and 3% sand. The % of described consistency of the fine material (Figure 12 shows that the unit is primarily soft to firm and the percentage of described density of the coarse material (Figure 13 loose to medium dense.

4.2.2.3 Standard penetration test

The consistency and relative density of the Paisley Clay Member are reflected in the standard penetration test vs distance from top of unit graph (Figure 25). It shows that there does not appear to be an increase in value with depth apart from a tendency of increased density in the sand samples.

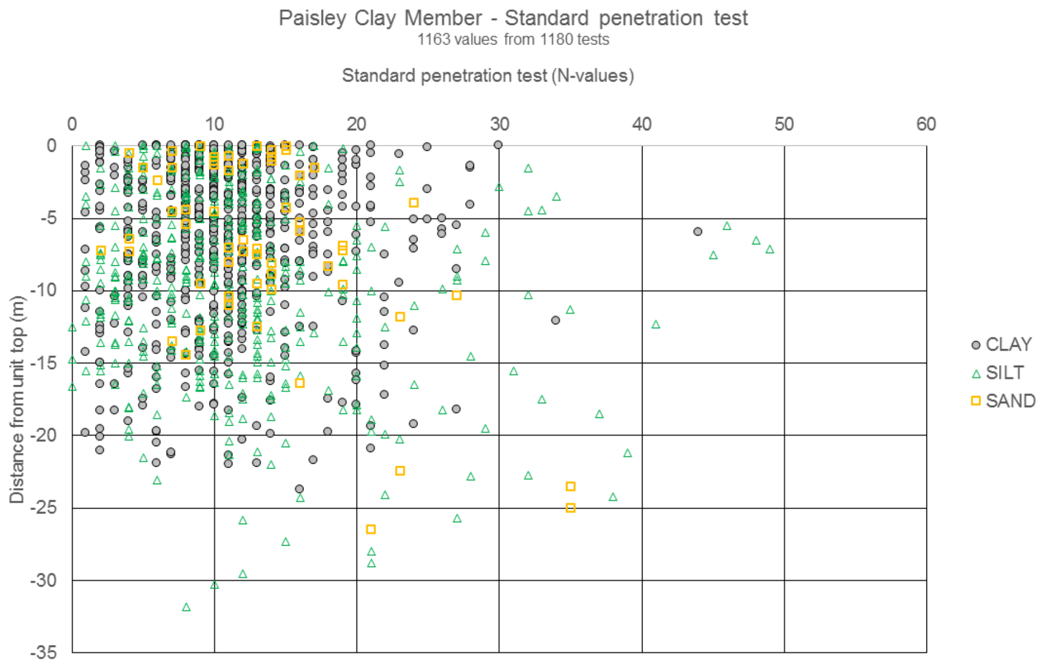

Figure 25. Paisley Clay Member - standard penetration test values vs distance from top of unit as recorded in existing borehole data.

4.2.2.4 WATER CONTENT

The water content mostly varies between 20% and 40% as shown in Figure 26. It is generally more variable near the top of the unit, which may be due to weathering/ climatic conditions at the time of sampling. In general, samples described as clay have a higher water content than silt, that is higher than sand. The lower values for sand might be due to draining during sampling/drilling in the field and in the laboratory, as sands drain and dry more rapidly than fine-grained samples. The variation in water content reduces with the depth.

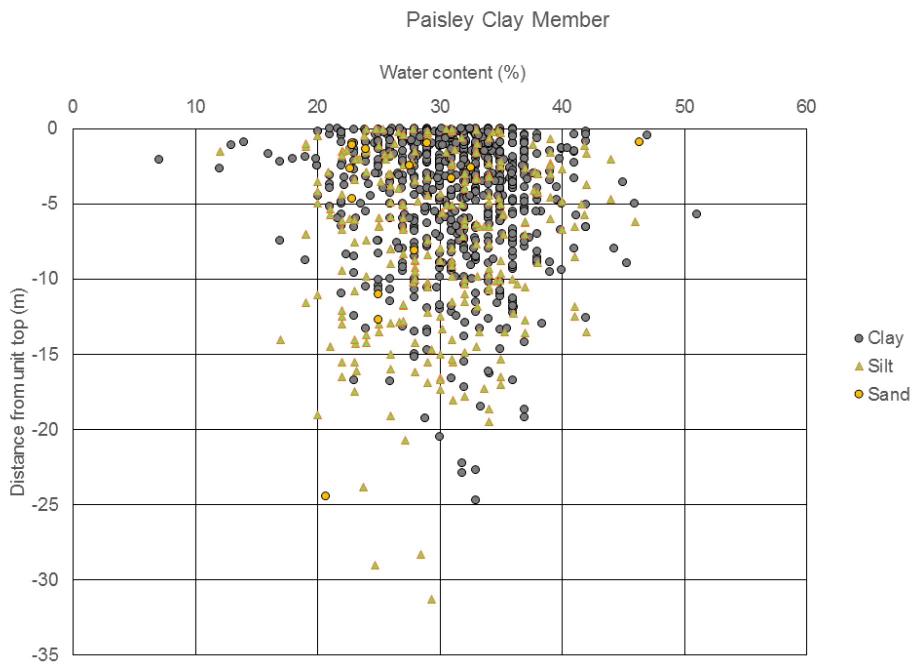

Figure 26. Paisley Clay Member- water content vs distance beneath unit top with described lithology recorded in existing borehole data.

4.2.2.5 BULK AND DRY DENSITY

The bulk density and dry density are plotted against distance from top of the unit in Figure 27 and Figure 28. Most of the bulk density values vary between 1.8 and 2.1 Mg/m^3. As with the water content, there tends to be more variability in the upper part. The minimum values generally increase with depth and clay samples tend to have slightly lower bulk density than silt samples, although there is a lot of overlap.

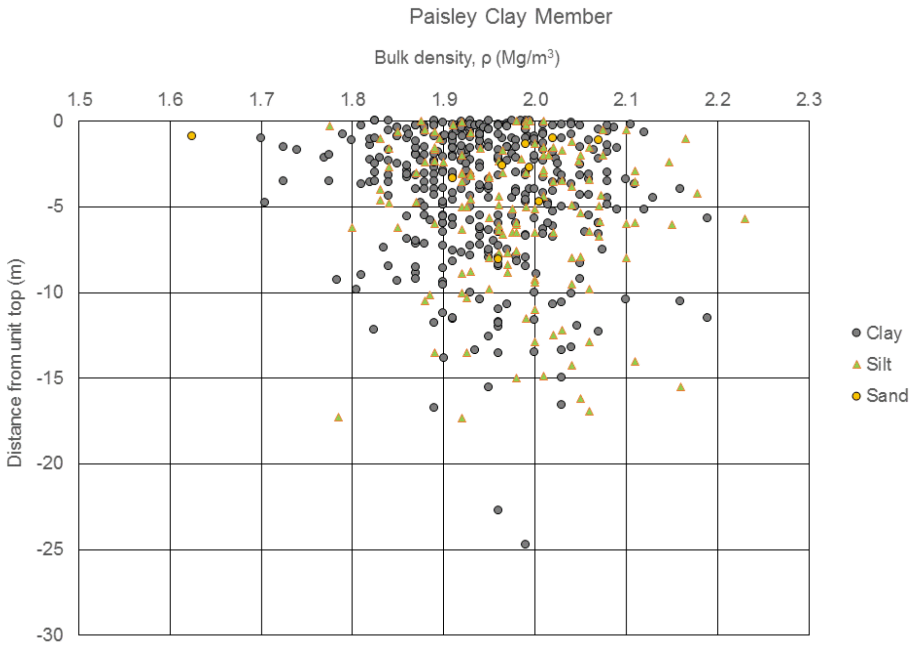

Figure 27. Paisley Clay Member- bulk density vs distance from top of unit recorded in existing borehole data

Most of the dry density values vary between 1.3 and 1.8 Mg/m^3. The distribution with depth below ground level (Figure 27) is similar to that of the bulk density, although there is a slightly more marked difference between silt and clay samples, silt tending to have slightly higher values than clay. This reflects the difference in water content as shown in Figure 26.

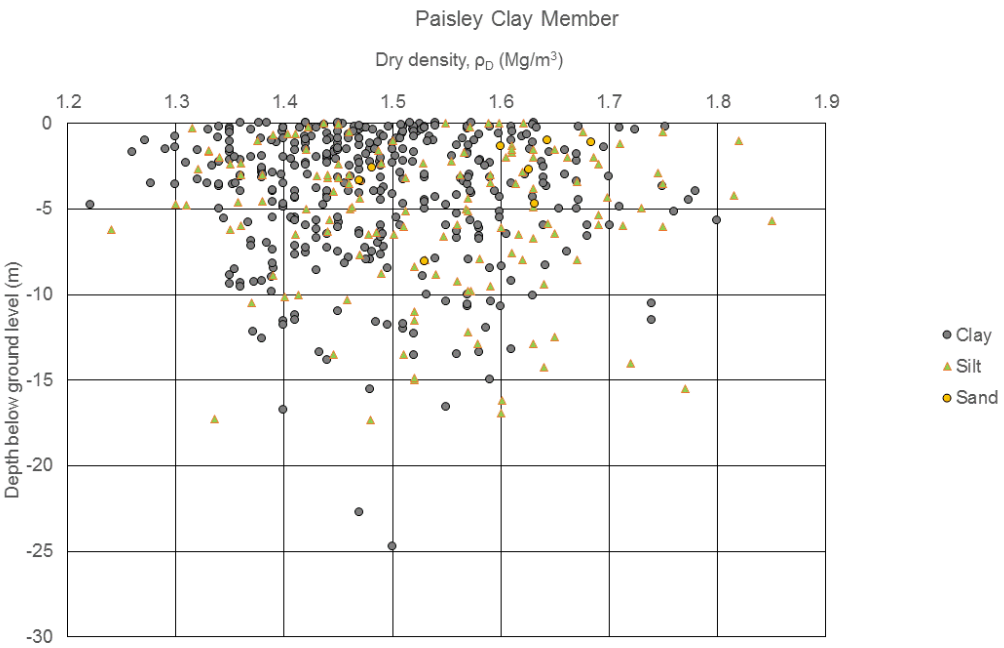

Figure 28. Paisley Clay Member- dry density vs distance from unit top

4.2.2.6 PARTICLE SIZE DISTRIBUTION

The particle size distribution of the Paisley Clay Member is shown as percentiles (Figure 29) as there are too many samples (number = 109) to plot individual lines. The plot shows that there is quite a wide range, reflecting the primary clay and silt with a smaller number of samples being fine to medium sand. A minority of samples contained a small amount of gravel.

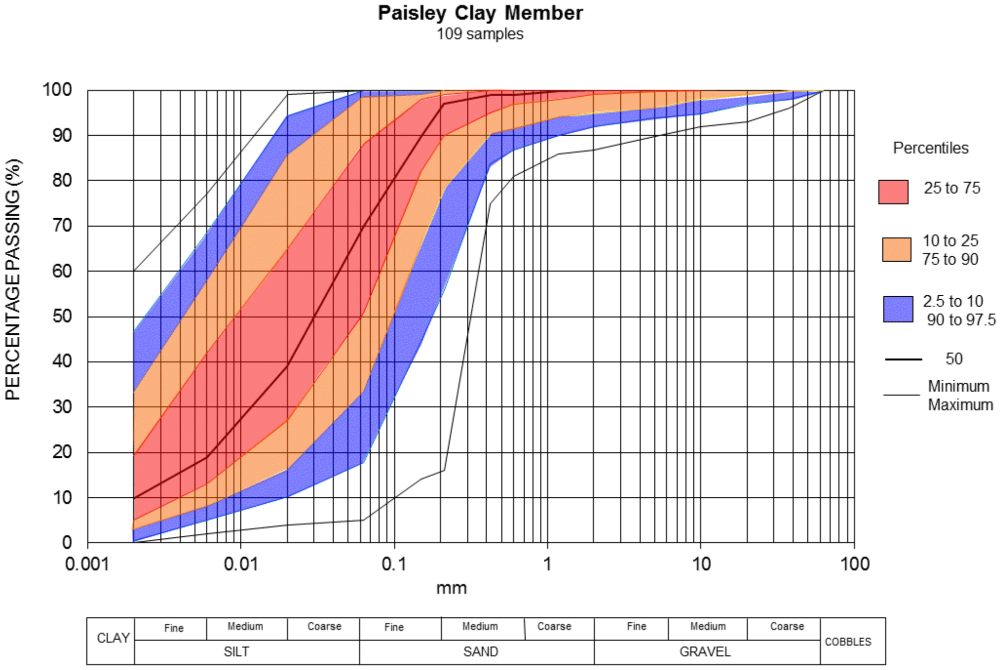

Figure 29. Paisley Clay Member- particle size distribution (percentiles) recorded in existing borehole data

The particle size distribution of laminated samples are measured on a bulk sample, which includes a number of laminations and so reflect a mix of materials.

4.2.2.7 PLASTICITY

The plasticity chart, Figure 30, shows that the Paisley Clay Member ranges from low to high plasticity with most of the 'silts' having low to intermediate plasticity. The described lithology shows that many of those materials described as 'silt' classify as clay, that is, above the A-line.

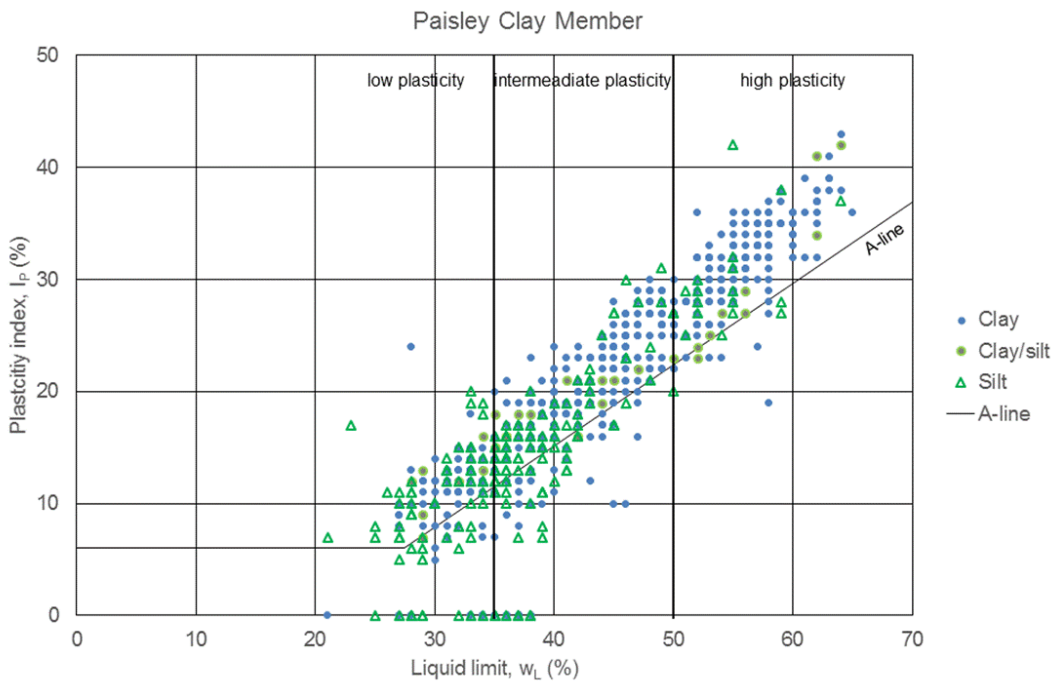

Figure 30. Paisley Clay Member- plasticity (Atterberg limit) chart

4.2.2.8 Undrained shear strength

The undrained shear strength data presented here is from triaxial tests only. The data is shown in Figure 31 plotted against depth from top of unit. Most of the values are between 5 kPa and 80 kPa and so classify as extremely low to high strength (BSI 2017). There appears to be little relationship between depth and strength, other than an increase in the lowest values with depth.

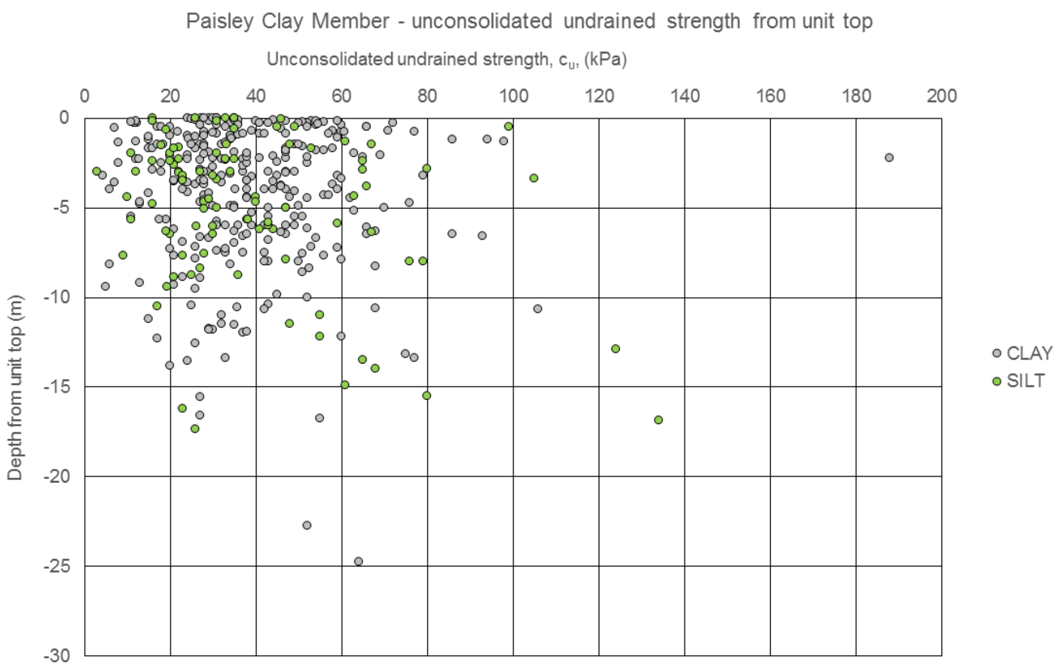

Figure 31. Paisley Clay Member- undrained shear strength vs distance from top of unit

4.2.3 Bridgeton Sand Member (BRON)

4.2.3.1 Introduction

The project 3D geological model shows that the Bridgeton Sand Member occurs to the north east (about 270 m) and north west (about 290 m) of the Cuningar Loop locations and to the northern side of Location 10 (nearest point about 340 m). Although unlikely to be present beneath the Locations, it is included here.

4.2.3.2 Description

In the Clyde Gateway area the Bridgeton Sand Member is generally a loose to dense, gravelly SAND sometimes with thin beds of clay, or silty slightly gravelly to gravelly SAND. Beds of GRAVEL and sandy GRAVEL and occasional beds soft to stiff sandy SILT also occur. Figure 11 shows that the main described principal soil type is sand, which makes up about 85% in this area and about 14% silt and with very minor principal clay and gravel.

4.2.3.3 Standard penetration test

The standard penetration test results are plotted against mean depth from ground surface in Figure 32 and plotted against distance below unit top in Figure 33. Figure 32 shows that there is an increase in values for the higher values with depth for the coarse-grained and that the values for gravel are generally higher values than sand and silt. Figure 33 shows less of an increase in SPT values with depth and that many higher values are near the top of the unit.

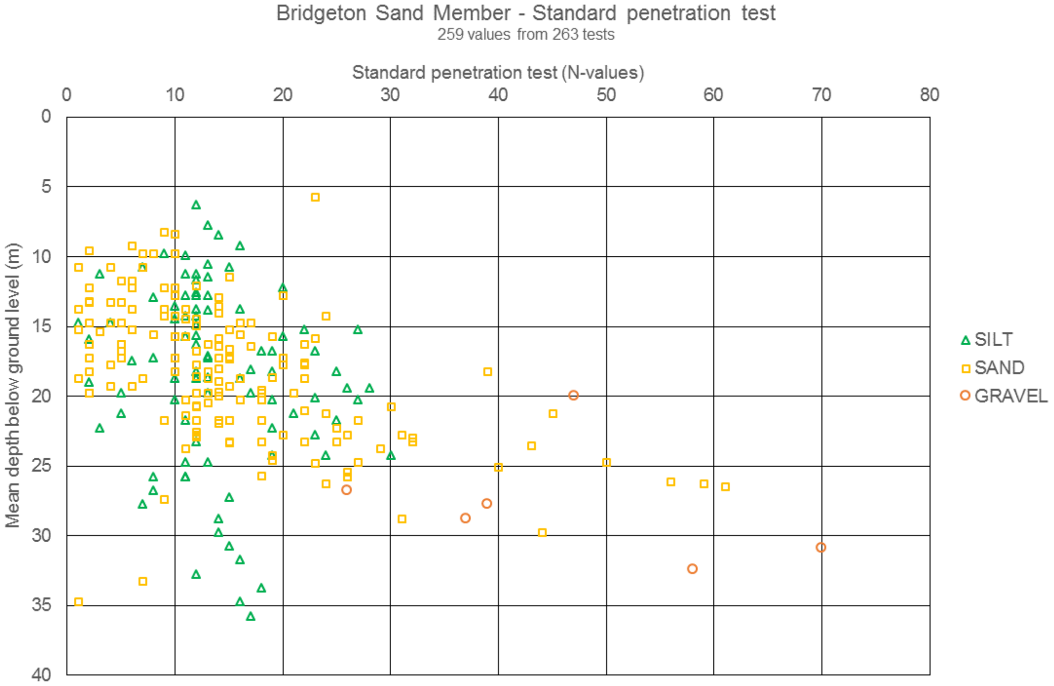

Figure 32. Bridgeton Sand Member standard penetration test N-values plotted against mean depth below ground level.

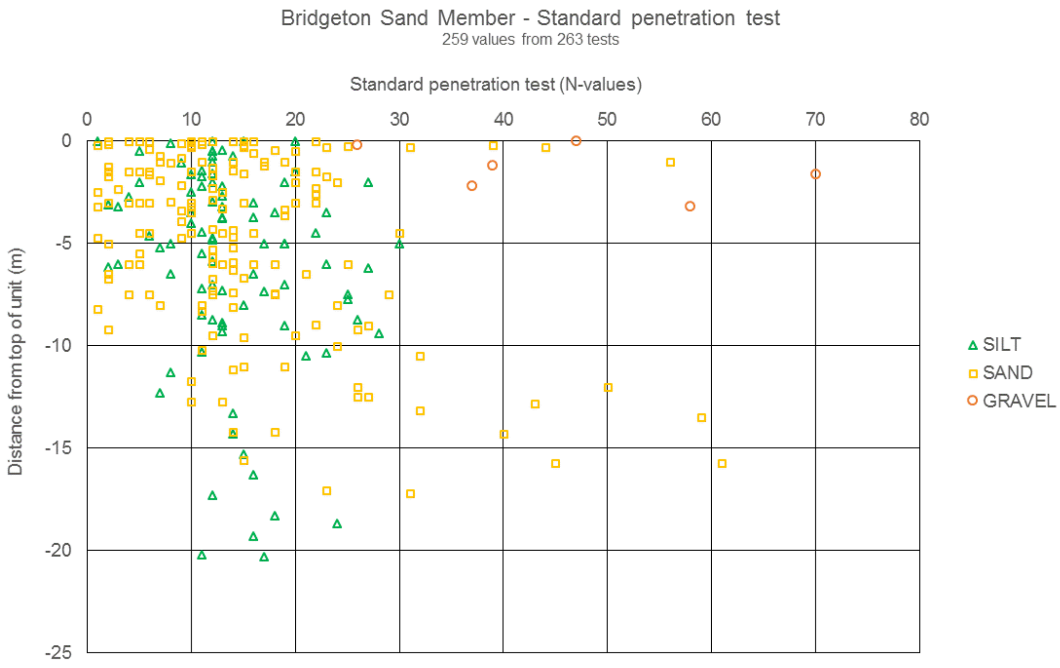

Figure 33. Bridgeton Sand Member standard penetration test N-values plotted against distance from unit top.

4.2.3.4 WATER CONTENT AND DENSITY

There is very little water content and density data as these measurements are rarely made on sand samples as undisturbed samples are difficult to take using standard pitting and drilling methods.

4.2.3.5 PARTICLE SIZE DISTRIBUTION

The particle size distribution of the Bridgeton Sand Member is presented as percentiles in Figure 34. It shows the unit is primarily a fine to medium sand, gravelly sand and, silty sand.

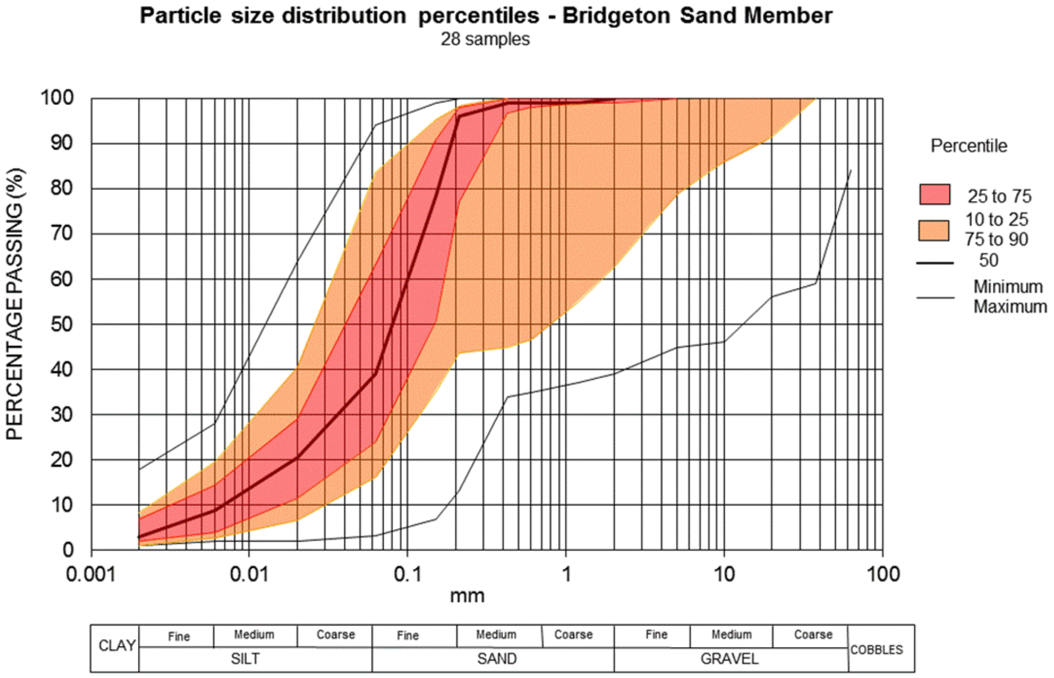

Figure 34. Particle size distribution of the Bridgeton Sand Member as percentiles.

4.2.4 Broomhouse Sand and Gravel Formation (BHSE)

The project 3D geological model shows that the Broomhouse Sand and Gravel Formation occurs close to Location 01 and within about 100 m of Location 10. Although unlikely to be present beneath the Locations, it is included here. The analysis does not include the Ross Sand Member, part of the Broomhouse Sand and Gravel Formation as it is not modelled near the locations.

4.2.4.1 Description

In the Clyde Gateway area the Broomhouse Sand and Gravel Formation is generally medium dense to dense brown sometimes grey SAND, gravelly SAND and medium dense to very dense sandy or silty sandy GRAVEL. Figure 11 shows that principal lithology is mostly sand with less than 30% of the unit described as gravel.

4.2.4.2 Standard penetration test

The standard penetration test N-values are presented against mean depth in Figure 35. The data shows that the Broomhouse unit in this area is very loose to dense. There is no apparent increase in N-value with depth. The same can be seen when the N-values are plotted against distance from the top of the unit (Figure 35).

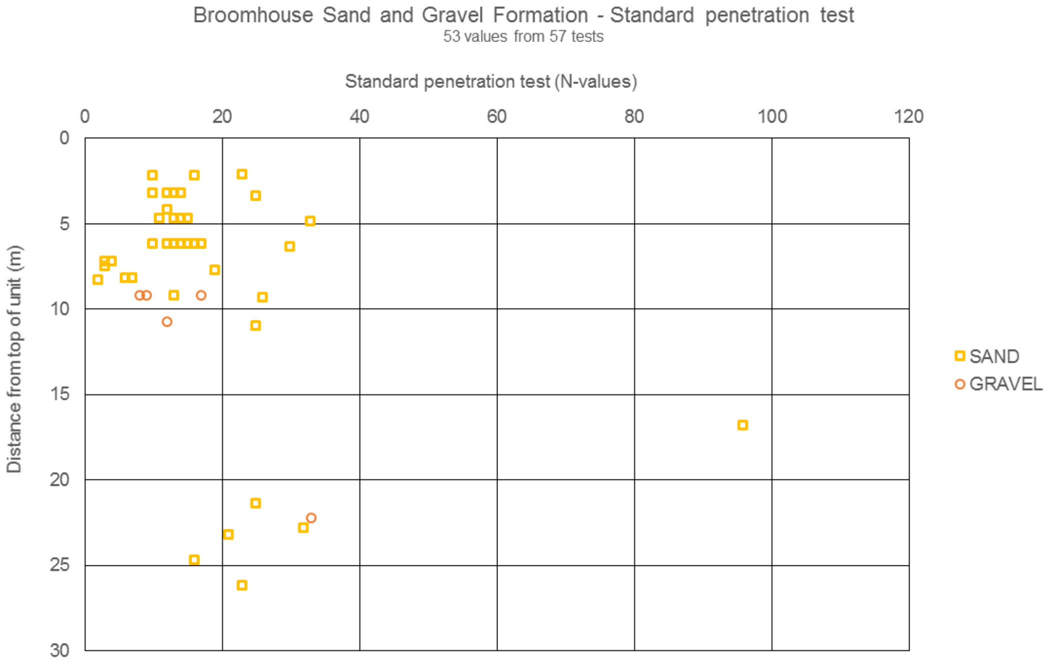

Figure 35. Broomhouse Sand and Gravel Formation Standard penetration test N-values plotted against mean depth below ground level.

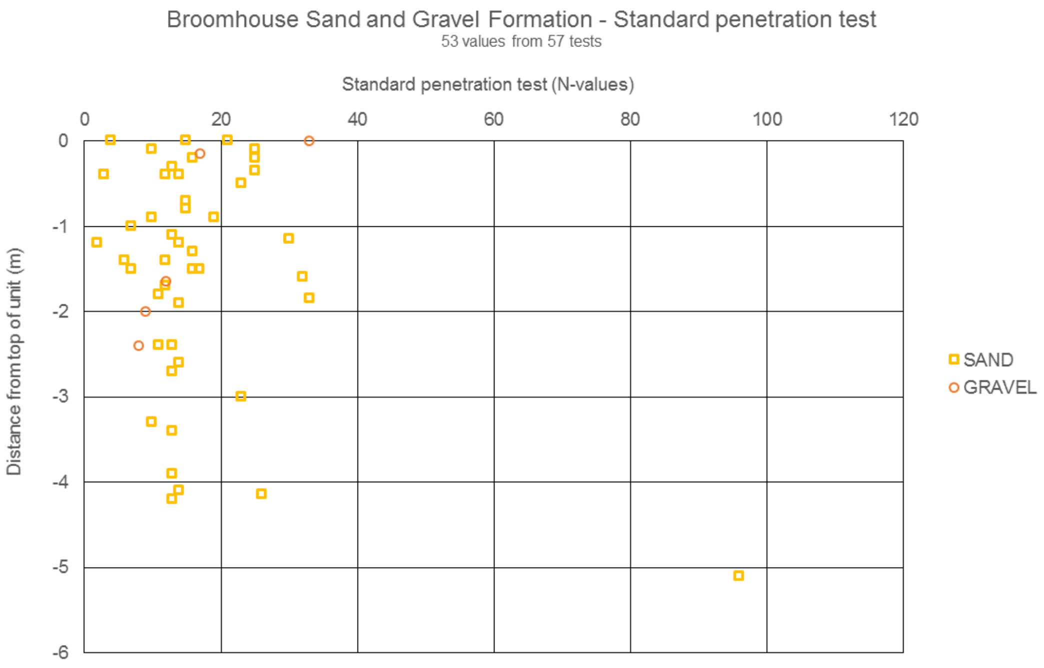

Figure 36. Broomhouse Sand and Gravel Formation Standard penetration test N-values plotted against mean depth below ground level.

4.2.4.3 WATER CONTENT AND DENSITY

As with the Bridgeton Sand Member there is little water content or density data and these parameters are not reported here.

4.2.4.4 PARTICLE SIZE DISTRIBUTION

As there are few particle size distribution test results in the area the individual test data are plotted in Figure 37. The plot shows two apparent populations, one a finer variably silty, gravelly SAND and the other a coarser silty sandy GRAVEL with one sample a slightly sandy, cobbley GRAVEL.

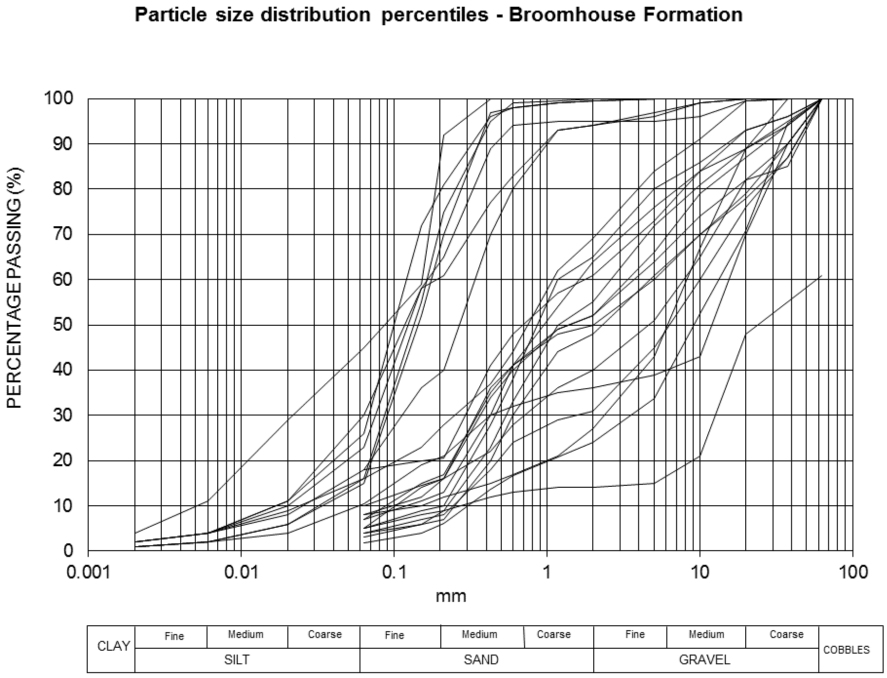

Figure 37. Broomhouse Formation particle size distribution

4.2.5 Wilderness Till Formation (WITI)

4.2.5.1 INTRODUCTION

The Wilderness Till Formation covers most of the Clyde Gateway area beneath the Paisley Clay Member. It is considered to have been deposited during the Dilmington Stadial (Late Devensian) (McMillan et al. 2010). It comprises mostly glaciotectonite but also with mostly thin glaciofluvial and glaciolacustrine local beds.

4.2.5.2 DESCRIPTION

The general lithology, consistency and density of the Wilderness Till Formation are presented as percentages in Figure 11, Figure 12 and Figure 13 respectively.

Clay with coarser particle to boulder size (glaciotectonite or Till)

The majority of the Wilderness Till Formation is firm to very stiff, sometimes extremely weak, occasionally soft near surface, reddish brown, greyish brown, dark brown, grey, sometimes mottled slightly to very gravelly slightly to very sandy CLAY (extremely weak MUDSTONE) or sometimes SILT sometimes with low cobble and boulder count. The gravel is usually fine to coarse and predominantly of Carboniferous sandstone, siltstone, basalt, limestone, coal and occasional other rock types. Cobbles are of sandstone, siltstone and mudstone with other minor rock types. Boulders are usually medium strong to strong sandstone, sometimes mudstone and limestone. Boulders tend to be more common in the lower part, including near rockhead and can be confused with bedrock.

Coarse-grained deposits

Borehole descriptions analysed here suggest that glaciofluvial (sand and gravel) beds make up about 7% of this unit in the Clyde Gateway area. There are a few, usually local, medium dense to very dense, brown, reddish brown, greyish brown, grey or dark grey SAND, gravelly SAND, sandy gravel or gravel beds. The individual coarse-grained beds are generally between 0.5 and

2 m thick occasionally up to 4 m thick. Thinner beds are described in general descriptions of the till.

Laminated clay and silt

Individual laminated clay and or silts beds are occasionally described in ground investigation pit and borehole logs and make up less than 1% of the Wilderness Till Formation in this area. The few beds described are generally less than 1 m thick but can be up to 4 m thick. They are generally firm to very stiff, laminated, brown, greyish brown to dark brown, sometimes slightly gravelly CLAY, sometimes with silt partings or SILT. Thin sand beds may be present. The gravel is usually fine to medium. Occasionally, within the laminated CLAY, there might be very thin beds of gravelly, sandy clay. Very thin beds of laminated clay/silt are described within the till.

4.2.5.3 Comments of the Wilderness Till Formation Geotechnical data

When considering the geotechnical data it is important to relate it to the borehole log description to differentiate between different possible depositional environments. This can be more difficult in glacial deposits, in particular where there are rapid changes in lithology. For example, the borehole log description might not relate to the sample tested, perhaps because of the limitations of the standard cable percussion sampling method used, i.e. 100 mm diameter thick-walled samplers (U100) where it is only possible to see the top or base of the sample. Alternatively, the lithology of the sample tested may be a minor component within the main description.

4.2.5.4 Water content

Water content is plotted against depth from the top of the Wilderness Till Formation in Figure 38. This shows that most of the water content values vary between about 7 and 18%. Values outside this range occur in the top 1 m of the unit.

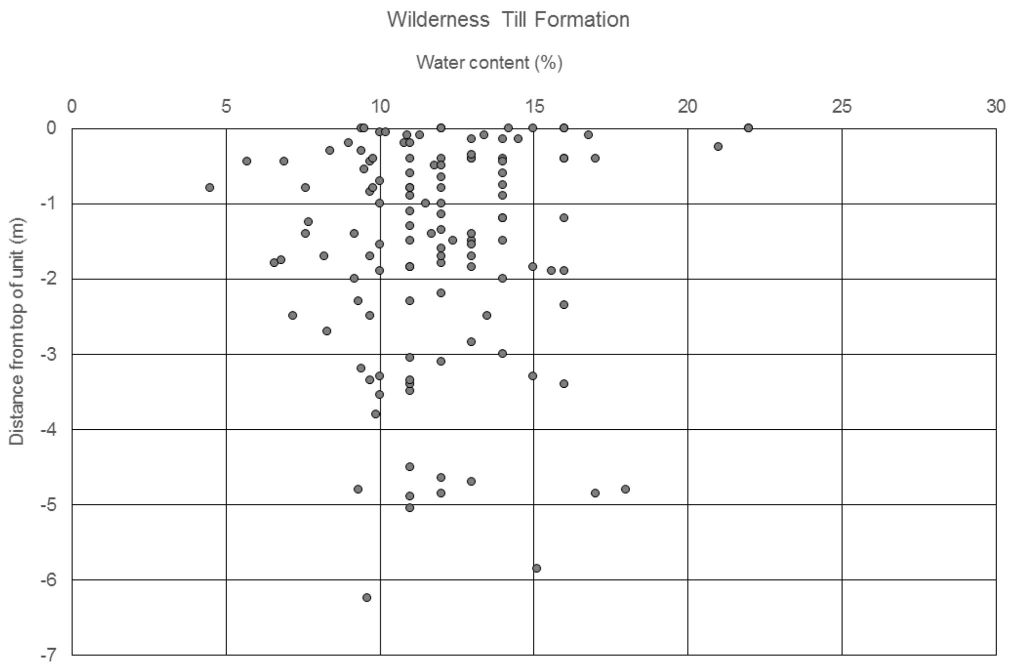

Figure 38. Wilderness Till Formation - water content vs distance from unit top.

4.2.5.5 Bulk and dry density

Bulk and dry density values are plotted against distance from the top of the unit in Figure 39 and Figure 40 respectively. The bulk density varies between about 2.0 Mg/m^3 and 2.4 Mg/m^3 and dry density between 1.8 Mg/m^3 to 2.2 Mg/m^3, the difference between the two densities reflecting the water content. As with the water content, those values outside the normal range are mostly within the top 1 m of the unit. There appears to be a reduction in density with depth, which would not be expected as it is usual for density to increase with depth in most fine-grained sedimentary materials. However, as the unit was primarily deposited beneath a glacier, the changes in density probably reflect the effective stress during and after deposition, including the effects of shearing, differences in pore pressure and normal load. The density values are very high for superficial deposits. This is due to the mode of emplacement and the wide range of particle sizes (see 4.2.5.6) in which the fine grains can infill between coarser particles producing the dense packing.

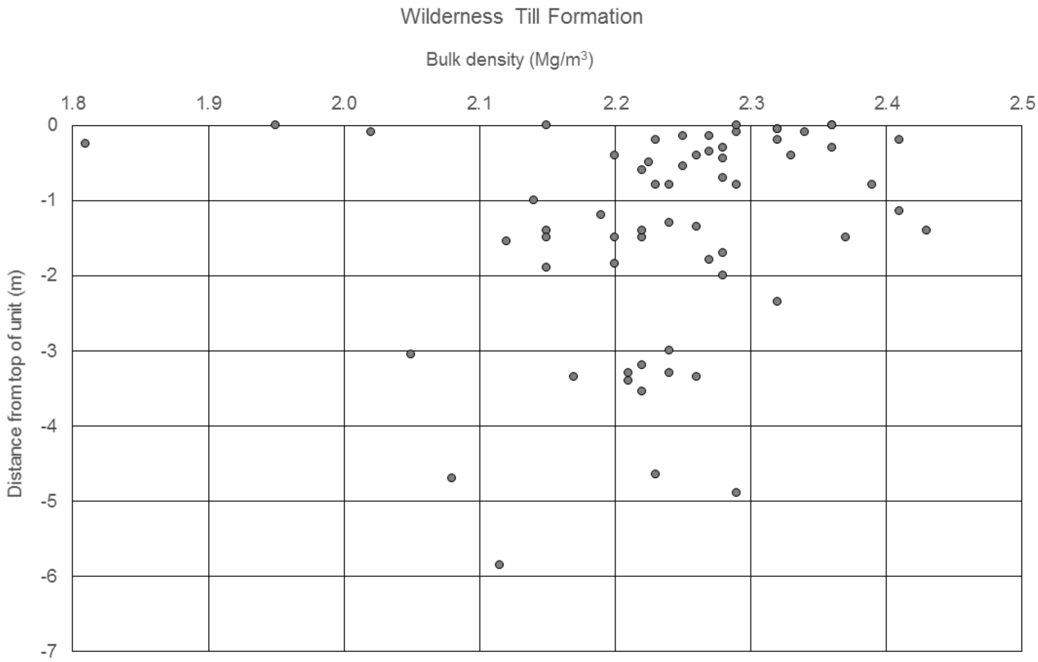

Figure 39. Wilderness Till Formation - bulk density vs distance from unit top recorded in existing borehole data

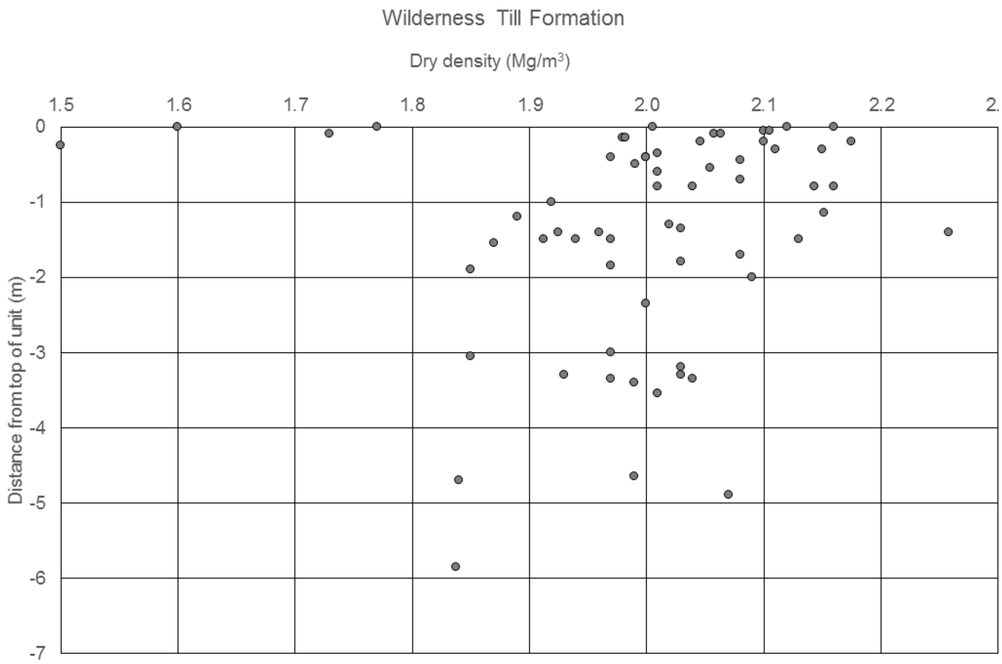

Figure 40. Wilderness Till Formation - dry density vs distance from unit top recorded in existing borehole data

4.2.5.6 PARTICLE SIZE DISTRIBUTION

The particle size distribution of the different lithologies are given separately, that is fine and coarse deposit (glaciotectonite; Figure 41), coarse-grained deposits (Figure 42) and fine-grained deposits in Figure 43. The first two graphs present the distribution data as percentiles as there are too many results to plot these individually. Particle size distribution in the laboratory is limited to sieves with 75 mm apertures. Also, the size of material is limited in boreholes to the diameter of the sampler.

The glaciotectonite (till) distribution shows the wide range of particle sizes and they are classified as well-graded or poorly sorted. Most of the samples tested contained some coarse-grained gravel to cobble-size particles.

Figure 41. Wilderness Till Formation - particle size distribution recorded in existing borehole data

The sand and gravel deposits varying from fine to medium sand to cobbles also commonly have a wide range of particle sizes, similar to the till. However, they have a smaller fine component (Figure 42). They are mostly well graded but with a small number of poorly graded samples. The distribution of the clay and silt deposit (glaciolacustrine) in Figure 43 are quite different from the other deposits of the Wilderness Till Formation as they are more poorly graded with some samples containing some gravel and occasionally cobble-size particles.

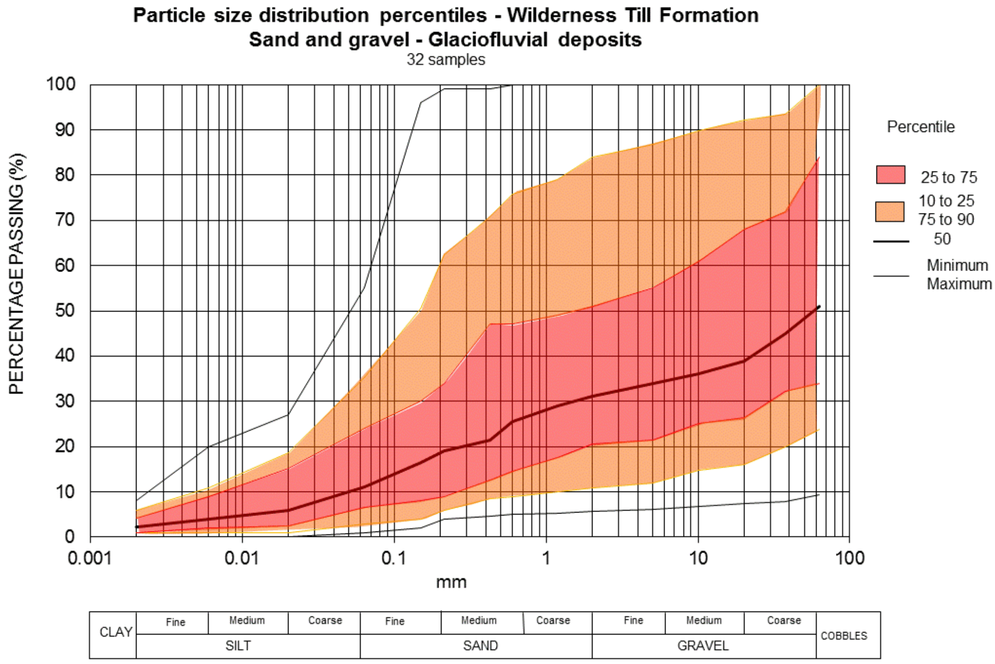

Figure 42. Wilderness Till Formation, sand and gravel deposits- particle size distribution recorded in existing borehole data

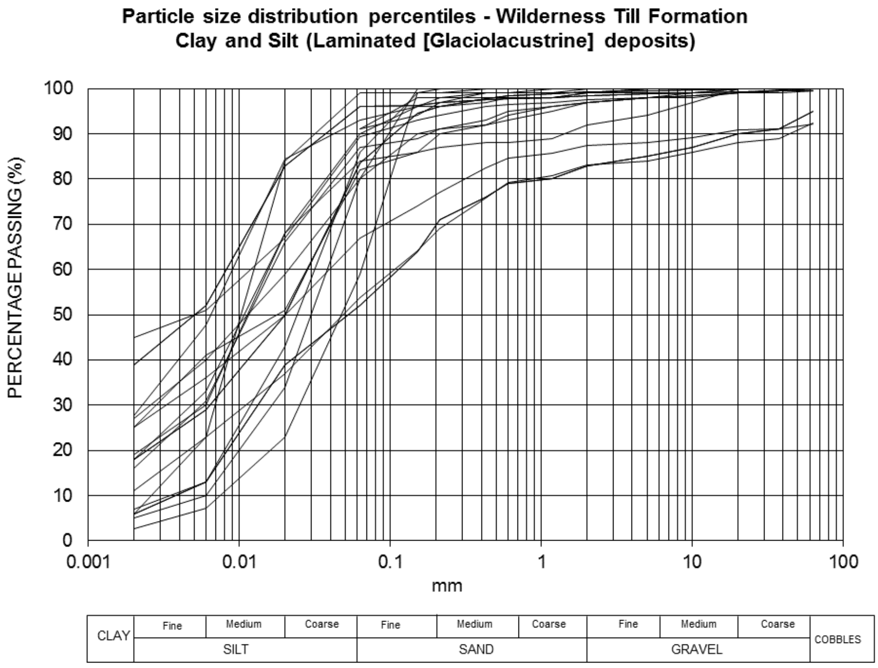

Figure 43. Wilderness Till Formation, laminated clay and silt - particle size distribution recorded in existing borehole data

4.2.5.7 PLASTICITY

The plasticity chart (Figure 44) shows a majority of the Atterberg limit values of the Wilderness Till Formation are low plasticity clay (liquid limit less than 35% and plotting above the A-line). Data from elsewhere in the Glasgow area show the unit to be primarily low to intermediate plasticity clay. The outlier, a high plasticity silt, is described as a typical glaciotectonite.

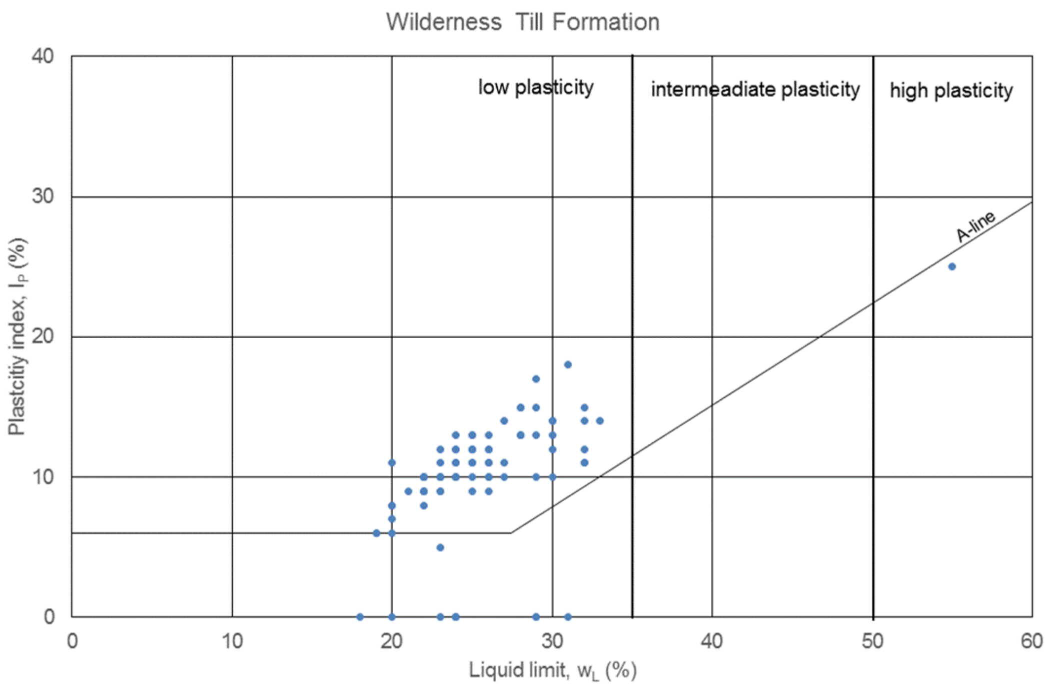

Figure 44. Wilderness Till Formation - plasticity chart recorded in existing borehole data

4.2.5.8 Standard penetration test

Standard penetration test N-values are plotted against the distance from the top of the unit in Figure 45. About two thirds of the tests were completed. The incomplete tests typically failed at an early stage with little penetration. This might be due to higher density or the presence of very coarse particles (cobbles and boulders). Also, many tests were abandoned at N-value = 50, which is a common practice. The unsuccessful tests were from 0 m to about 15 below the top of the unit.

Of the successful tests Figure 45 shows that most N-values between 20 and 60 with the largest variation in the top 4 m.

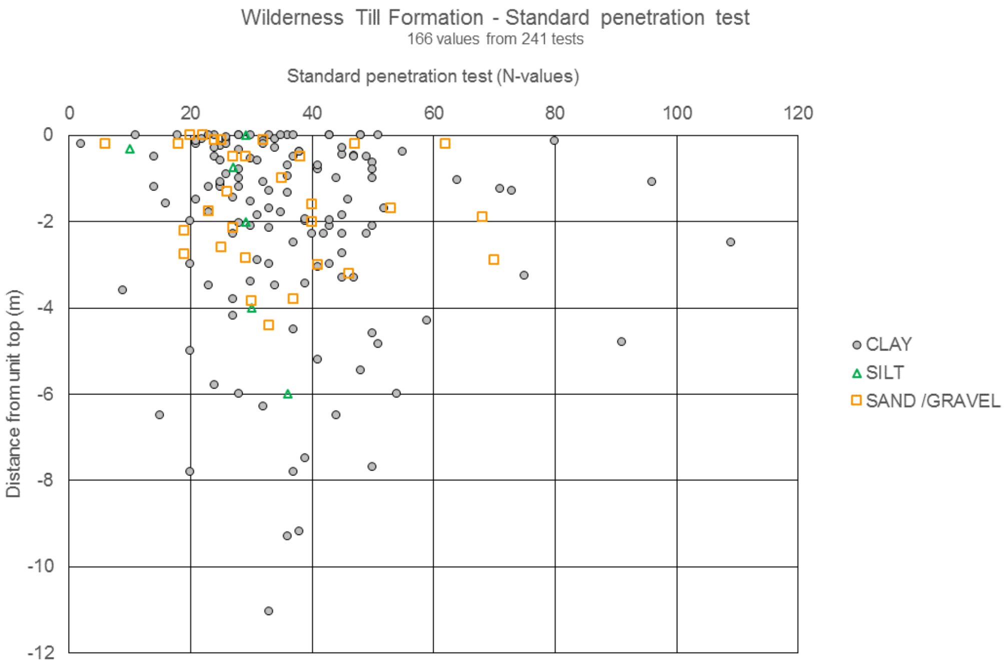

Figure 45. Wilderness Till Formation - standard penetration test vs distance from unit top with described lithology recorded in existing borehole data

4.2.5.9 Undrained shear strength

The undrained shear strength data considered here relate only to standard triaxial tests carried out on three different samples at different confining stresses.

The results are plotted against distance from unit top in Figure 46. There is a wide range of values, generally from 20 kPa to 300 kPa. There appears to be a population at about 120 kPa and below, and one 150 kPa and above. The bulk density vs undrained shear strength plot (Figure 47) shows an increase in strength with density but there are a large number of points with higher bulk density and lower undrained shear strength. This might be due to natural structures within the sample but could also be due to sample disturbance during field and laboratory sampling. Typically, field sampling of fine-grained samples has been carried out using a thick-walled sampler and cable percussion drilling method, which, due sample disturbance, is no longer considered a suitable sampling method for strength and deformation tests (BSI 2006).

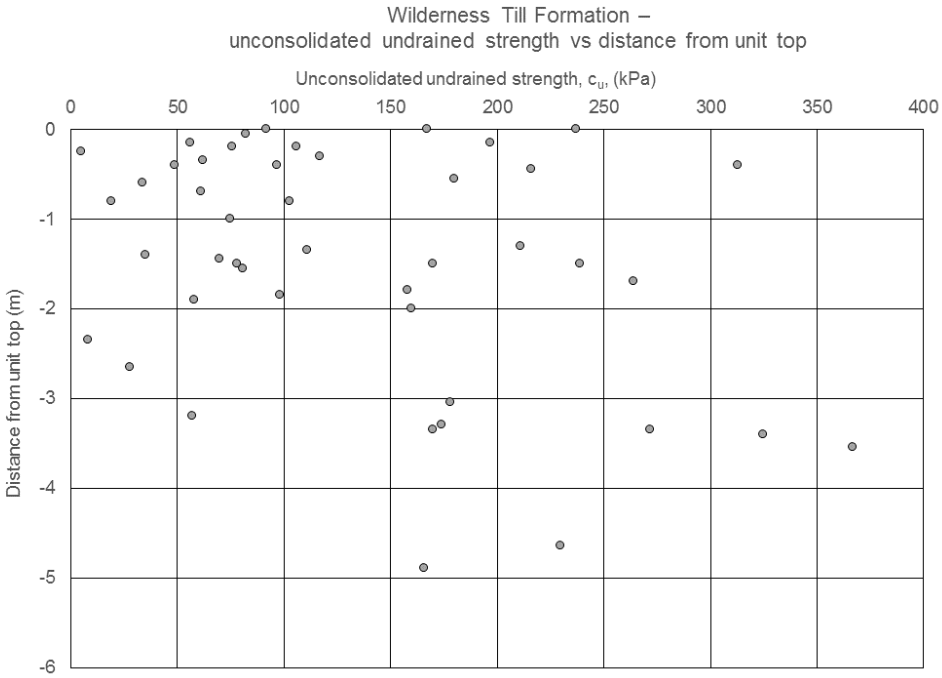

Figure 46. Wilderness Till Formation - triaxial undrained shear strength vs distance from top of unit strength recorded in existing borehole data

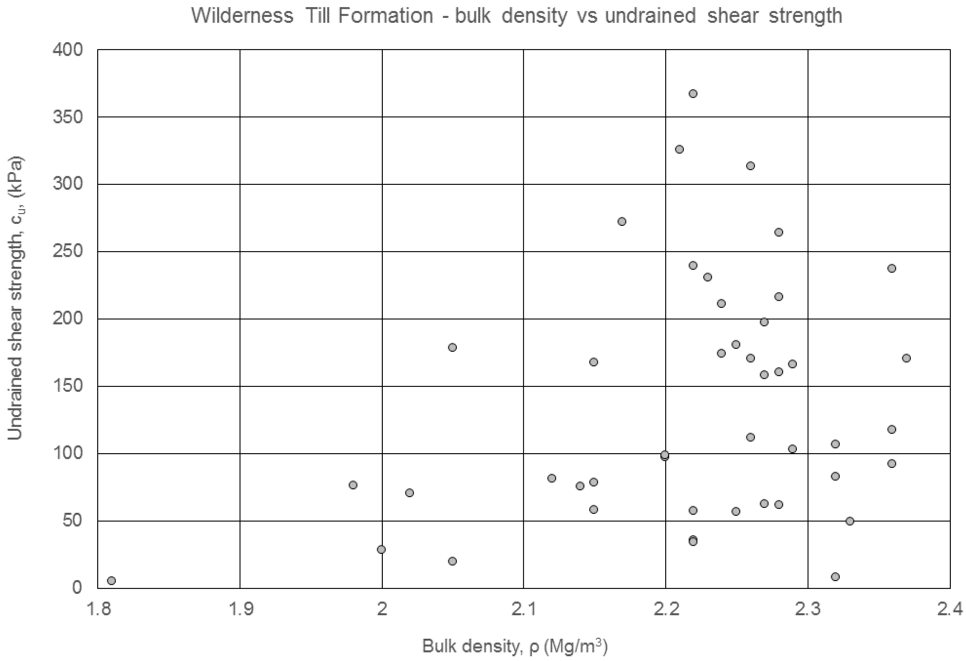

Figure 47. Wilderness Till Formation - bulk density vs. undrained shear strength recorded in existing borehole data

4.3 BEDROCK

The target units are the Scottish Middle Coal Measures and Scottish Lower Coal Measures formations and the mine workings within them. The igneous sills of the Midland Valley Carboniferous to Early Permian Alkaline Basic Sill Suite occur in the area, and are known to be present within the Scottish Lower and Middle Coal Measures Formation to the north of the area and within the Limestone Coal Formation south of the Dechmont Fault. Although sills are not expected to be intercepted by the proposed boreholes, they have been included here. The age and depositional environment of the units are listed in Table 15 and the relative percentage of the different described lithologies from existing borehole data in the Coal Measures units are in Figure 48. The Middle Coal Measures Formation tends to contain a higher percentage of mudstone and siltstone, slightly more coal and less sandstone than the Lower Coal Measures Formation. Sandstone makes up the greatest percentage being over 50% of the Lower Coal Measures Formation and a little over 40% of the Middle Coal Measures Formation.

The Midland Valley Carboniferous to Early Permian Alkaline Basic Sill Suite is mostly described in ground investigations as dolerite or sometimes basalt and 'white trap'.

Table 15. Bedrock units

Lithostratigraphical unit and code	Age	Depositional environment
Scottish Middle Coal Measures Formation (MCMS)	Carboniferous Duckmantian Substage	Wet land forest, floodplain, river and deltaic distributary channels, prograding deltas and shallow lakes. Occasional thin marine beds.
Scottish Lower Coal Measures Formation (LCMS)	Carboniferous Langsettian Substage	Wet land forest, floodplain, river and deltaic distributary channels, prograding deltas and shallow lakes. Occasional thin marine beds.
Midland Valley Carboniferous to Early Permian Alkaline Basic Sill Suite (MCPAS)	Permian Cisuralian Epoch to Carboniferous Westphalian Stage	Intrusive igneous

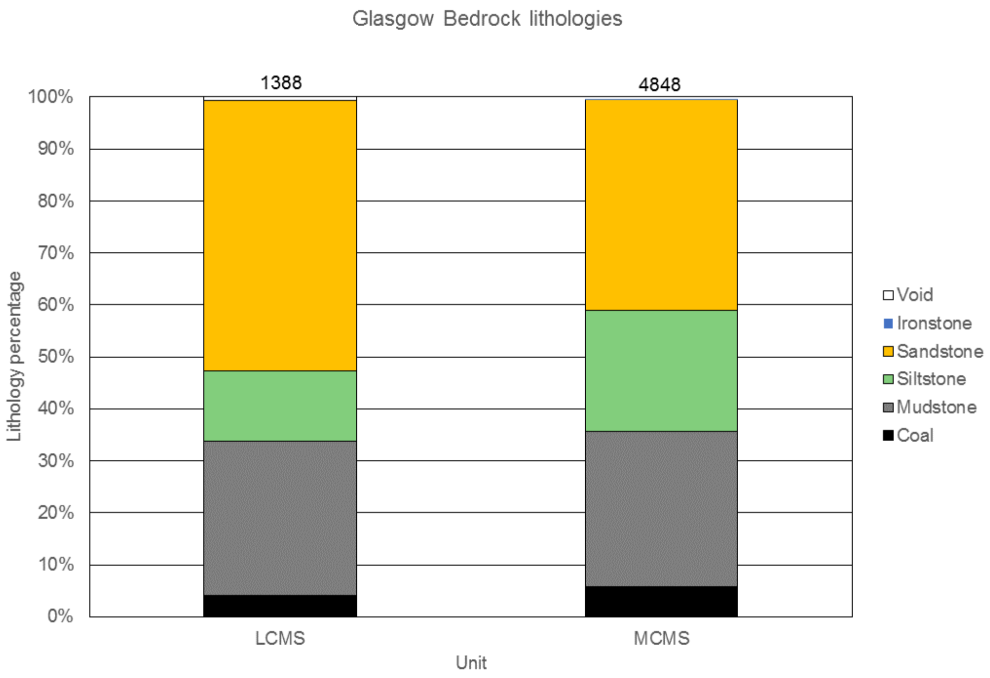

Figure 48. Middle and Lower Coal Measures formations- percentages of lithologies recorded in existing borehole data. Sample lengths in metres at top of each column.

The percentage of described strength are shown in Figure 49. The percentages of strength of the Scottish Lower and Middle Coal Measures formations are similar, mostly being weak to medium strong, whereas the Midland Valley Carboniferous to early Permian Alkaline Basic Sill Suite (MCPAS) rocks are mostly medium strong to extremely strong.

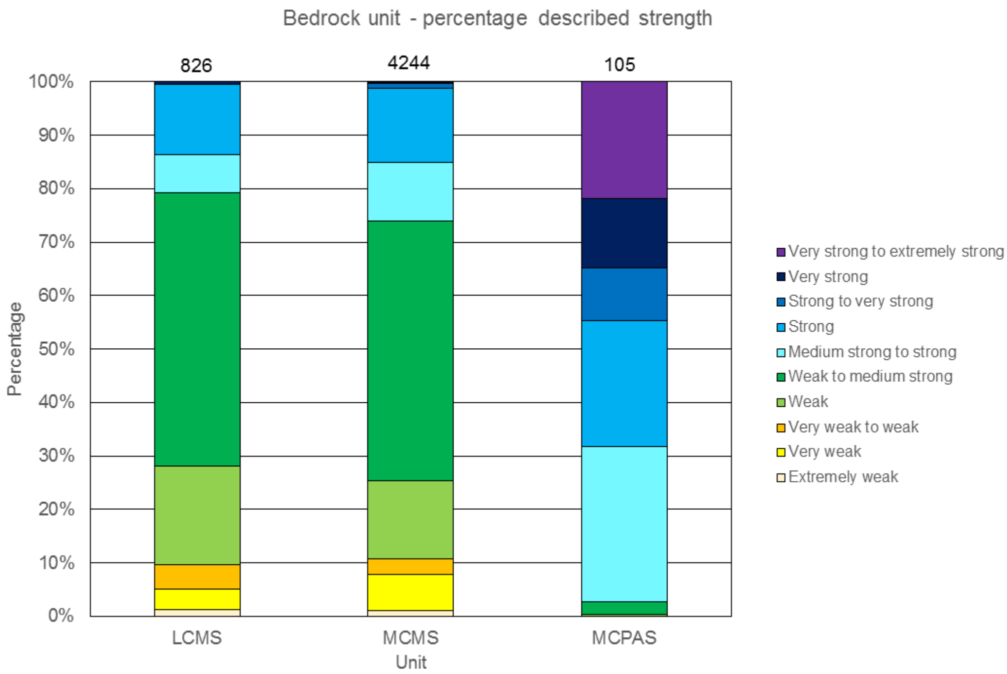

Figure 49. Bedrock units - percentage described strength. Sample in metres at top of each column.

4.3.1 Scottish Middle Coal Measures Formation

4.3.1.1 Introduction

The data on the Scottish Middle Coal Measures Formation presented here are from the Clyde Gateway area.

4.3.1.2 Description

Interface between the Wilderness Till Formation and Scottish Middle Coal Measures Formation

Identification of the base of the Wilderness Till Formation and the top of the Scottish Middle Coal Measures Formation can be very difficult. The basal Wilderness Till Formation can comprise sand and gravel deposits in some areas, although they are not in the 3D geological model in this area. If these deposits are glaciofluvial deposits then they are likely to contain more rounded gravel and cobbles and have varied lithology, not just that of the top of the bedrock. Also, the top of the bedrock may have been disturbed by the glacier. Good description is required, unfortunately, many of the descriptions from some ground investigations do not contain enough information to distinguish between the superficial deposits and disturbed or weathered bedrock. Also, boulders are more prevalent towards the base of the Wilderness Till Formation and can be mistaken for bedrock.

Rotary drilling is usually used to progress boreholes in rock where samples are required for engineering description and testing. However, cable percussion drilling is also used in the upper part of the bedrock with standard sampling tools or hydraulic pick. This might be done to identify whether bedrock has been reached or a boulder. When this is done, weaker rock can be broken up and described as gravel rather than 'as the material is in situ' as should be the case.

This results in difficulty in identifying bedrock or superficial deposits and likely errors in classification.

Soil-like materials

The greatest thickness of soil-like ‘weathered’ bedrock is generally less than 2 m thick and occurs in a few boreholes. Examples are given below:

Medium dense gravelly SAND with a low cobble and boulder content,

Very dense grey sandy medium to coarse angular to subrounded GRAVEL of siltstone with clay pockets.

Very dense sandy angular fine to coarse GRAVEL of sandstone.

Engineering bedrock

The bedrock comprises mudstone, siltstone and sandstone with minor ironstone, coal and seatearth. There are also strata of interbedded mixed lithologies where the change in rock type cannot be sensibly separated in the description for instance:

‘MUDSTONE with IRONSTONE bands;

‘MUDSTONE and SANDSTONE bands;

‘thinly to thickly laminated interbedded silty MUDSTONE, SILTSTONE and fine grained micaceous SANDSTONE’

‘Light grey, fine grained SANDSTONE, with thin beds of dark grey mudstone’

With this in mind the following are typical descriptions of the different lithologies.

Assessing the strength of the bedrock is often best done from the descriptions. In general, there are few field strength tests (point load test) or laboratory strength tests (unconfined compressive strength) carried out. Also, the preparation and testing of weaker materials is often difficult or impossible and so there tends to be a bias towards stronger rocks. The percentage of described strength of the Scottish Middle Coal Measures Formation for each lithology is shown on Figure 50.

Figure 50. Scottish Middle Coal Measures Formation – percentage of described strength for the unit and its lithologies. The sample length size in metres is above each column.

Mudstone

The mudstone is described as varying between extremely weak and strong, however, it is mostly weak to medium strong.

It is occasionally strong or extremely weak to very weak, sometimes laminated, usually light to dark grey, sometimes carbonaceous or with fossil plant remains, occasionally shelly, MUDSTONE, sometimes SEATEARTH, occasionally with thin bands of siltstone, sandstone or ironstone.

The extremely weak to very weak material is sometimes near the top of unit but can be at depth and is sometimes seatearth or fireclay or described as ‘weathered’ even though it is at depth below the top of the unit. The strong rocks are sometimes ‘irony’ or ‘carbonaceous’ or pyritic.

Siltstone

Similar to mudstones, the siltstones are usually weak to medium strong but sometimes extremely weak to very weak or strong.

It is, sometimes laminated, thinly to thickly bedded or unbedded, light to dark grey sometimes black, sometimes with plant remains such as stems and roots, SILTSTONE occasionally with thin laminations of ironstone, mudstone or sandstone.

As with mudstones, there does not appear to be relationship between strength and the distance from the top of the unit as strong rocks are found near the top of the unit and extremely weak rocks at depth. Strong siltstone is sometimes described as ‘irony’ or with sandstone laminae.

Sandstone

Sandstones are generally stronger than either mudstones or siltstones, being usually weak to strong with some very strong beds and only occasionally very weak.

It is generally thickly to very thickly bedded but sometimes laminated to medium bedded and with silty laminae, white to light grey, sometimes light brown or orange brown, very occasionally mottled purple and grey, fine to medium SANDSTONE with occasional plant remains.

Very weak sandstone is usually found at the top of the unit and strong rock might be present at any depth below unit top.

Coal

Generally very weak to weak, sometimes medium strong, or extremely weak, sometimes laminated, black COAL.

As with mudstone and siltstone there does not appear to be any relationship between strength and distance to the top of the unit as extremely weak coal is found at depth and weak to medium strong coal is present near the top of the unit.

Ironstone

Ironstone makes up a very small proportion of the Scottish Middle Coal Measures Formation but is also present as laminations or very thin beds in other lithologies.

It is generally very strong, sometimes extremely strong, thinly bedded to ‘massive’, light grey to dark grey or greenish brown or grey and brown, sometimes sandy IRONSTONE.

There is no relationship between strength and position below unit top.

4.3.1.3 Uniaxial compressive strength

As with the previous units, there are a limited number of laboratory strength tests. The uniaxial compressive strength test results, plotted in Figure 51, show that most of the tested samples were sandstone with few siltstone and mudstone samples tested. This might be due to the requirements of the ground investigations or that siltstone and mudstone samples were not successfully sampled or prepared. The Figure indicates that there is no relationship between distance from the top and strength. The saturation state of the samples when tested is not known. The data shows that the sandstone varies between weak and very strong (BSI 2015) as in the description.

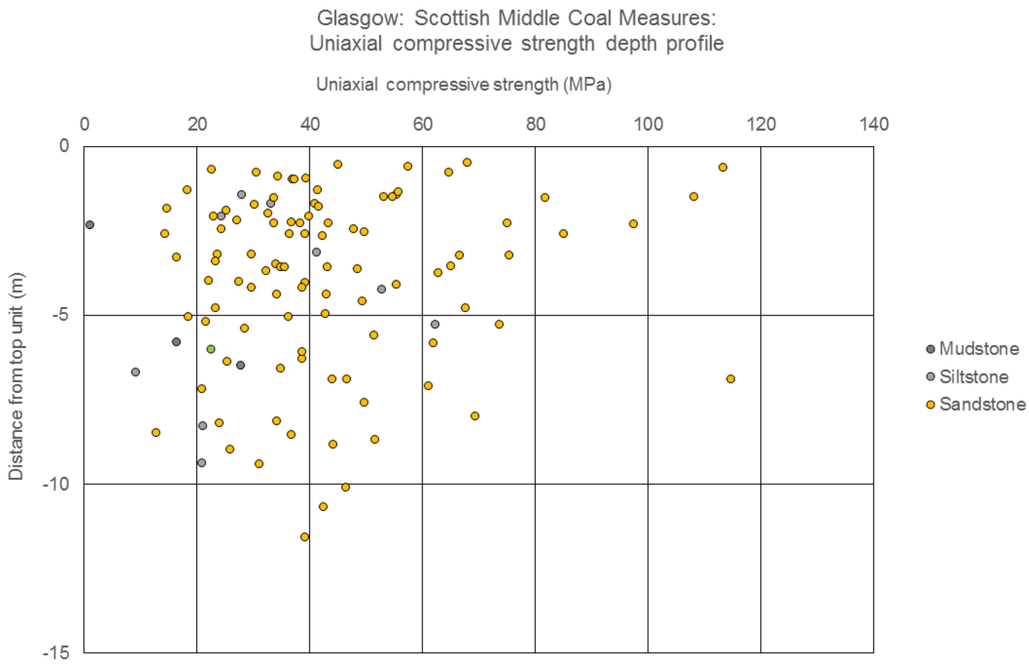

Figure 51. Scottish Middle Coal Measures Formation - uniaxial compressive strength vs distance from the top of the unit with lithology.

4.3.1.4 DISCONTINUITY STATE

The behaviour of the rock mass, including rock mass strength and secondary groundwater movement are controlled in part by mechanical discontinuities or joints and faults. The discontinuity state of rotary core is classified using four quantitative parameters. These are total core recovery (TCR), solid core recovery (SCR), rock quality designations (RQD) and fracture character as fracture index, FI (fracture per metre, 1/m) or fracture spacing I_F (mm), which is often given as maximum, median and minimum fracture spacing. TCR, SCR and RQD should be measured for each core run and the fracture character should be measured on material of similar fracture ‘character’ and so could be for part of a core run or represent several core runs. The definition of each parameter is in BSI (2015). The joints or fractures that should be considered are those that probably existed in the ground. Those breaks that are induced by drilling, handling or due to core drying out etc. should be discounted. Natural joints might be identified by their character, dip and whether there is staining or evidence of water movement. However, it is not possible to identify from existing ground investigation datasets whether the identification was done correctly. It is commonly found that the number of ‘joints’ is over estimated because breaks along bedding planes, particularly for mudstones, are induced by the various operations of sampling, handling, transport and storage.

In this report total core recovery, rock quality designation and fracture index are considered.

The percentage of total core recovery, as indicated in Norbury (2016), and rock quality designation are given in Table 16. They are also plotted from the unit top in Figure 52.

Table 16 shows that nearly 89% of core runs provided over 75% of total core recovery and, therefore, in accordance to Norbury (2016), can be used to provide a fully described dataset. Mudstone has the lowest recovery. Rock quality designation shows that only about 8% core runs provided very good quality core and 20% good quality core. There are differences between the lithologies. About 15% of sandstone is classified as very good quality core and 40% good to very good quality core, whereas, mudstone has much lower percentages of only 2% very good quality and 8% good to very good quality core.

Table 16. Scottish Middle Coal Measures Formation – rock quality designation vs distance from top of unit with nominal lithology.

Unit of nominal lithology	Total core recovery % (n = 1431)			Rock Quality Designation % (n = 1316)			
	>75	>50	>25	>90	>75	>50	>25
Scottish Middle Coal Measures Formation	89%	94%	97%	8%	20%	45%	63%
Mudstone	80%	87%	97%	2%	8%	25%	46%
Siltstone	92%	98%	99%	5%	17%	43%	68%
Sandstone	91%	95%	98%	15%	40%	65%	82%
Coal	94%	96%	98%	2%	3%	11%	18%

Figure 52 shows that lower total core recovery occurs within the top 5 m of the unit, and most of the lower values for sandstone were in this zone, whereas the values for mudstone are less sensitive to the distance from unit top.

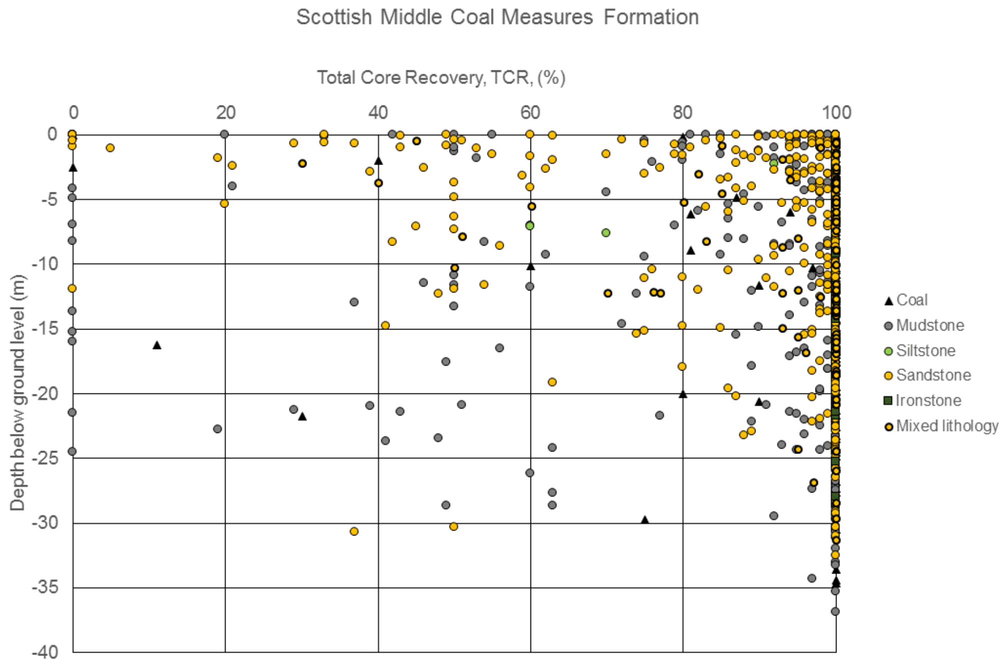

Figure 52. Scottish Middle Coal Measures Formation – total core recovery vs distance from top of unit with nominal lithology.

The rock quality designation plot (Figure 53) shows that, in general, the RQD of sandstone tends to increase with distance from unit top. This is less marked for siltstone and mudstone.

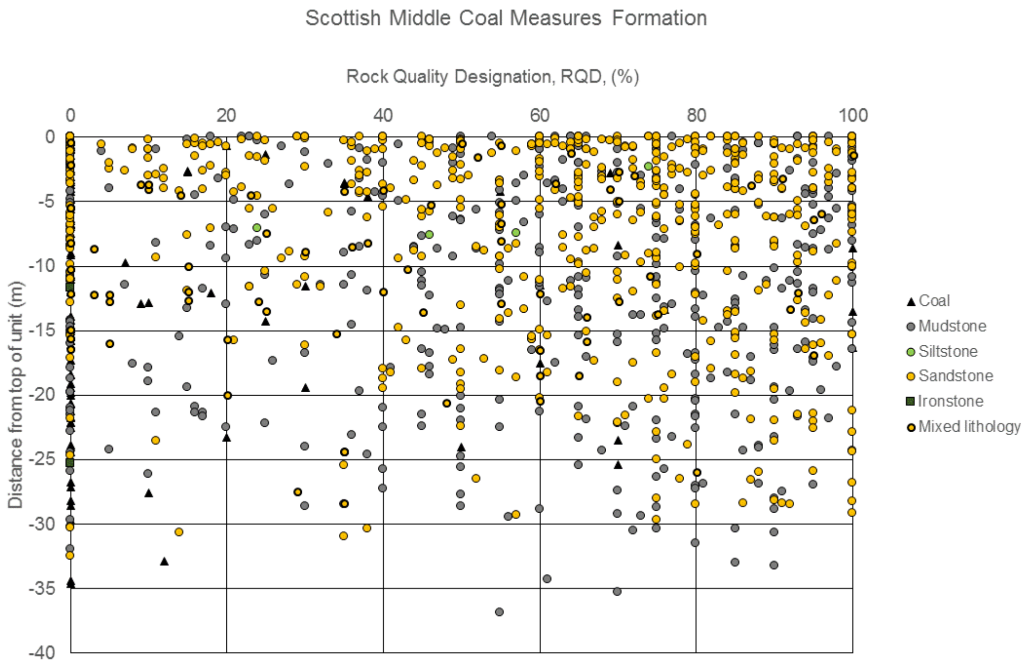

Figure 53. Scottish Middle Coal Measures Formation - rock quality designation vs distance from top of unit.

Fracture index

The fracture index, FI, is measured as the number of fractures or joints per metre and should not be confused with fracture spacing, which is measured in mm. Both sets of data are present in the BGS National Geotechnical Properties Database but as there are more data available for fracture index, this parameter presented here. The middle or median fracture spacing value is recalculated from mm to 1/m, thus increasing the number of values. Non intact rock, generally recovered as gravel, is generally coded as -1 in the National Geotechnical Properties Database.

Fracture index and fracture spacing should be described for zones of similar discontinuity spacing and character and so should relate more closely to the lithological description than TCR or RQD, which are per core run.

The fracture index unit is 1/m: lower fracture density tends towards 0 and non-intact core tends towards high values. Some ground investigations classify non-intact core as 99 and within the National Geotechnical Properties Database a value of -1 is given, which is also sometimes used in industry. However, for practical reasons the default value '99' is for non-intact core, which accounts for the cluster of points at FI = 99 on Figure 54. A further cluster of points at FI = 25 indicates that this has been reported as a default value for very closely to closely spaced discontinuities.

The sandstones in this formation tend to have lower Fracture Index values than the other rock types and FI values decrease with depth below the top of the unit (Figure 54). Although this is the case for other rock types, it is less marked for mudstones, which also has higher value (greater than 25 fractures) at depth, indicating very closely spaced discontinuities.

As with rock quality designation, fracture index values show that sandstone tends to be better quality rock than the other rock types. The number of discontinuities tend to reduce with depth and this is more marked in sandstones.

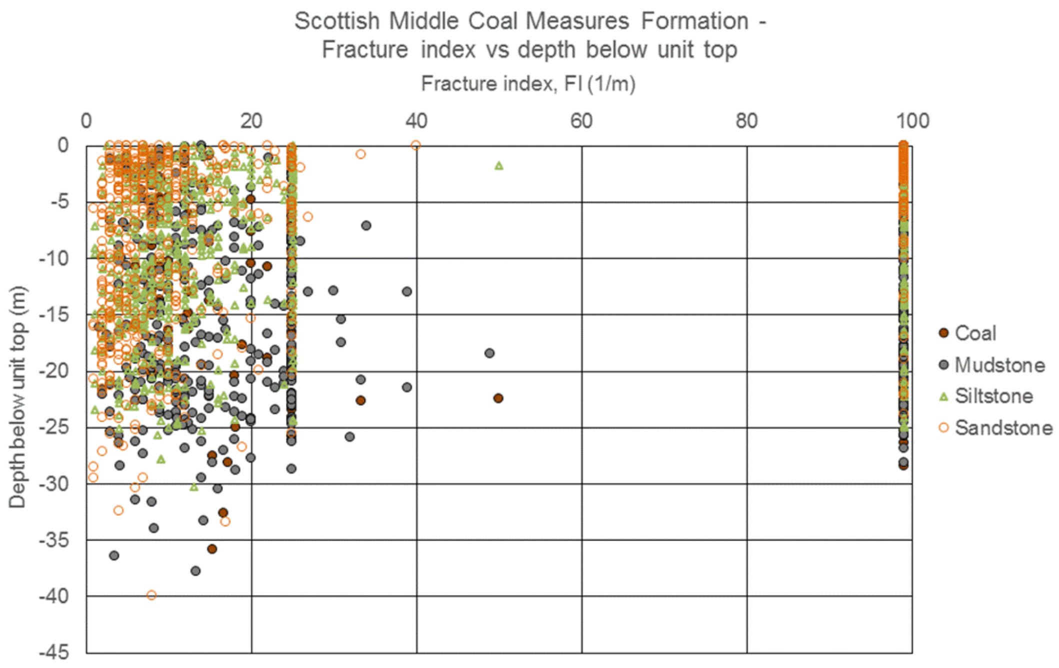

Figure 54. Scottish Middle Coal Measures Formation - fracture index vs distance from top of unit with lithology.

4.3.2 Scottish Lower Coal Measures Formation

4.3.2.1 Introduction

The Scottish Lower Coal Measures Formation is likely to be present at depth below the Scottish Middle Coal Measures Formation and is prognosed to be encountered in the deepest borehole at Location 10. Ground investigations have not been drilled to this depth and so there is no data in the National Geotechnical Properties Database for the unit buried beneath the Scottish Middle Coal Measures Formation. Therefore, the data presented here, for the Scottish Lower Coal Measures Formation is for guidance only and are taken from a nominal 10 m below the top of the Scottish Lower Coal Measures Formation, which is considered to be below most of the effects of weathering from surface. The data is from a wider area of investigation and includes the four map sheets NS56SE, NS56NE, NS66SW and NS66NW.

4.3.2.2 Description

The percentage of described lithology is shown in Figure 55. The graph shows that a majority of the Lower Coal Measures Formation is sandstone (over 50%), then mudstone (about 30%), siltstone (about 14%) and coal (4%), with minor ironstone.

Overall, the Scottish Lower Coal Measures Formation is weak to medium strong with about 14% strong and about 1% very strong (Figure 55). The sandstone tends to be stronger, weak to strong, than siltstone and mudstone weak to medium strong. Coal is generally very weak to weak.

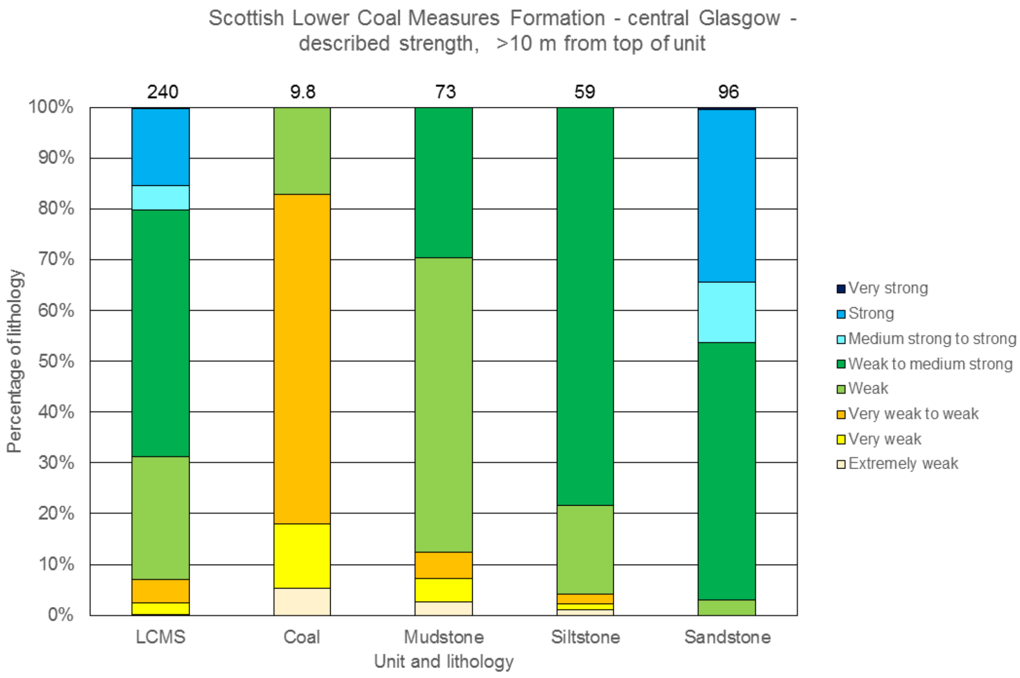

Figure 55. Scottish Lower Coal Measures Formation - described strength at > 10 m from unit top for unit and lithology

Mudstone

Very weak to medium strong, occasionally extremely weak (seat earth), sometimes thinly laminated to medium thick bedding, light to dark grey to black, sometimes carbonaceous MUDSTONE and SEAT EARTH sometimes with ironstone nodules and plant remains.

Siltstone

Weak to medium strong, occasionally extremely weak to very weak, thinly laminated, to sometimes medium bedded, grey, occasionally brown SILTSTONE or SEAT EARTH, occasionally with mudstone or sandstone laminations or bands.

Sandstone

Weak to strong, sometimes very strong, laminated to thickly bedded, white, light grey, occasionally brownish grey, occasionally silty or muddy SANDSTONE occasionally with mudstone or siltstone laminae or bands, occasional ironstone nodules.

Coal

Very weak to weak, sometimes extremely weak, sometimes thinly bedded, black COAL.

4.3.2.3 Uniaxial Compressive Strength

As stated earlier, there is a generally a bias towards testing the stronger rocks and those that are more easily prepared (i.e. mostly sandstones). The limited number of uniaxial compressive strength tests are plotted against the distance from the top of the unit (Figure 56). Unfortunately, all the available data are for samples collected within the top 10 m of the unit, which might have been affected by weathering. The data show that the samples are classified as very weak to strong SANDSTONE. There appears to be a slight increase in the strength of the weakest samples with depth as there are no very weak samples from more than 5 m below the top of the unit. There are insufficient data for siltstone and mudstone to provide any comments.

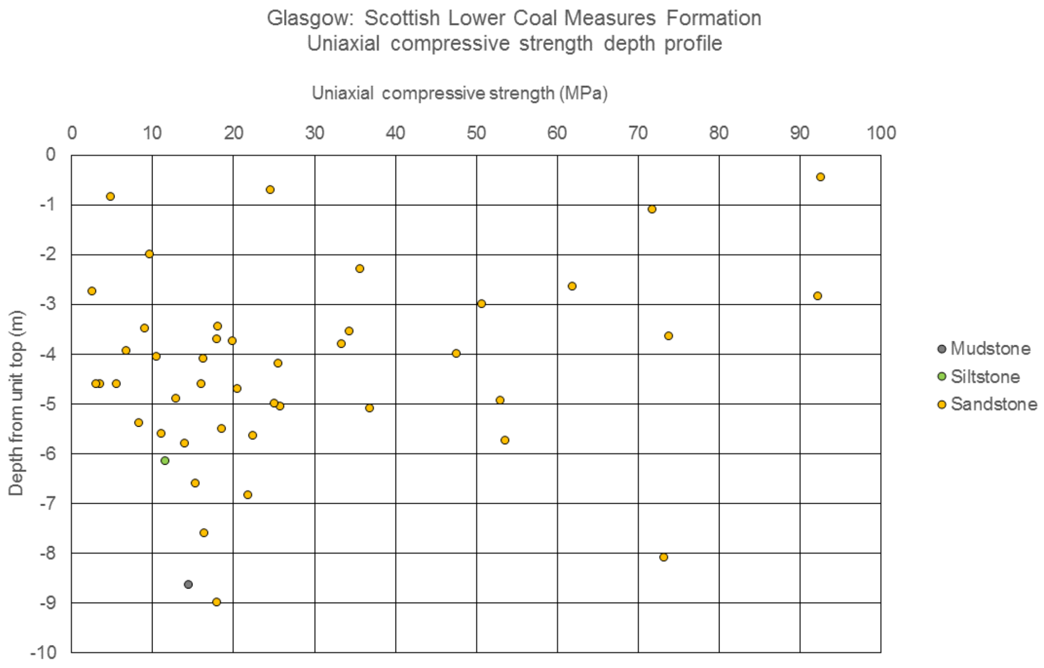

Figure 56. Scottish Lower Coal Measures Formation - uniaxial compressive strength plotted against distance from unit top with lithology.

4.3.2.4 TOTAL CORE RECOVERY AND ROCK QUALITY RECOVERY

The data presented here are for samples collected more than 10 m below the top of the unit (see 4.3.2.1).

The total core recovery data and rock quality designation statistics are presented in Table 17. They do not include mined zones and packed waste. The total core recovery is high with over 96% of data having a TCR of higher than 75%. However, in the data for RQD only 8% are classified as very good rock and 23% good to very good rock and over 50% of the rock is poor or very poor.

Table 17. Lower Coal Measures Formation - total core recovery and rock quality designation statistics for specific parameter value.

Parameter	Total core recovery %			Rock Quality Designation %			
Parameter value	>75	>50	>25	>90	>75	>50	>25
% of values	96.5%	98%	99%	8%	23%	45%	62%

As the TCR values are generally high, in the plot of TCR against distance below the top of unit (Figure 57) TCR is over 90% in most cases. However, the equivalent plot for rock quality designation (Figure 58) shows that the sandstone tends to be good to very good rock, whereas all siltstone is classified as very poor rock, coal is generally very poor or very good rock and mudstones are more variable.

Figure 57. Scottish Lower Coal Measures Formation - total core recovery against distance below the top of the unit with nominal lithology.

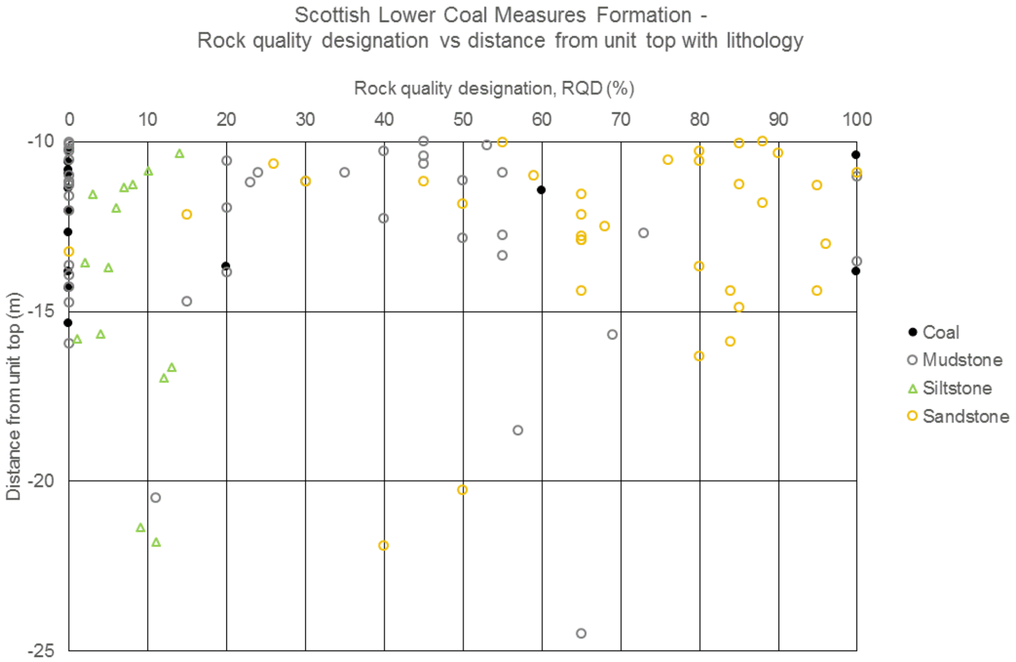

Figure 58. Scottish Lower Coal Measures Formation – rock quality designation against distance below the top of the unit with nominal lithology.

4.3.2.5 Fracture Index

The fracture index is plotted against depth below unit top in Figure 59. There does not appear to be any relationship between fracture index and depth. This indicates that the selected data are not or are little affected by weathering. Most of the values are less than 20/m, which includes most of the values of siltstone and sandstone. These values are shown in more detail in Figure 60. This graph shows that most sandstone values are less than 10/m, whereas most of the mudstones are more than 10/m and the values for siltstone are between 4/m and 16/m.

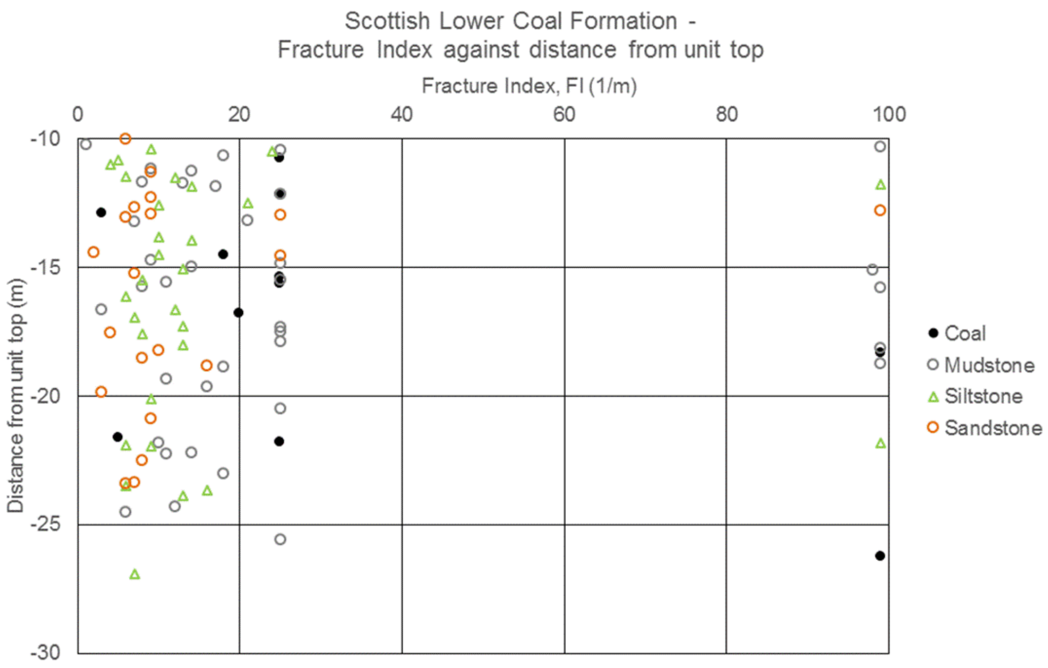

Figure 59. Scottish Lower Coal Measures Formation – fracture index against distance below the top of the unit with lithology.

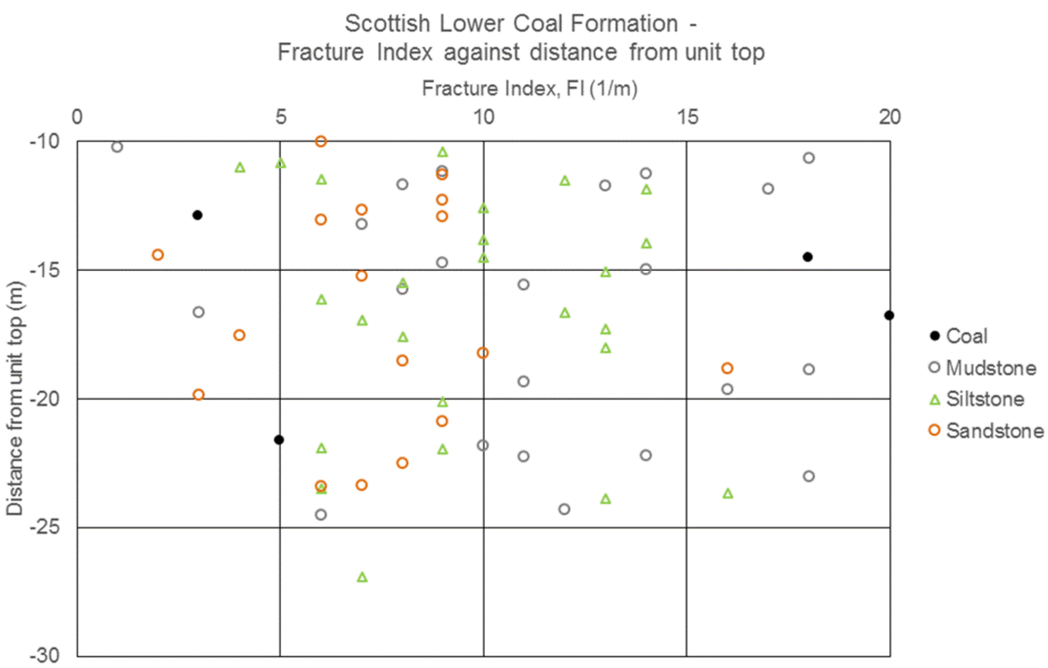

Figure 60. Scottish Lower Coal Measures Formation – fracture index against distance below the top of the unit with lithology for FI values of less than 20/m.

4.3.3 Midland Valley Carboniferous to Early Permian Alkaline Basic Sill Suite (MCPAS)

4.3.3.1 Introduction

The data is for the map sheets NS56SE, NS56NE, NS66SW and NS66NW.

4.3.3.2 Description

There is limited information on this unit. The described strength is indicated in Figure 49 as being medium strong to extremely strong.

It is generally described as:

Strong to very strong, sometimes medium strong to extremely strong, fine to medium, greenish grey or grey to dark grey BASALT or DOLERITE.

Moderately strong to strong, greenish grey pyroxene QUARTZ-DOLERITE with narrow veins of quartz or pyrite mineralisation.

Medium strong to very strong porphyritic DOLERITE, which is sometimes light grey.

Some of the dolerite is described as 'slightly weathered'. Sometimes this is in bands within the unit.

4.3.3.3 UNIAXIAL COMPRESSIVE STRENGTH

The uniaxial compressive strength, plotted with distance from unit top (Figure 61), shows two populations; one of weak to strong rock and the other of very strong to extremely strong rock. The lower strength rock samples are often described as slightly weathered, or with calcite veins, or both, or with chilled margins. Some rock is described as strong or very strong but the uniaxial compressive strength test values are classified as being weak to medium strong. This might be due to failure through weakened parts of the test sample, such as along calcite veins. Those samples that are very strong to extremely strong (>100 MPa) are described as grey-green quartz dolerite.

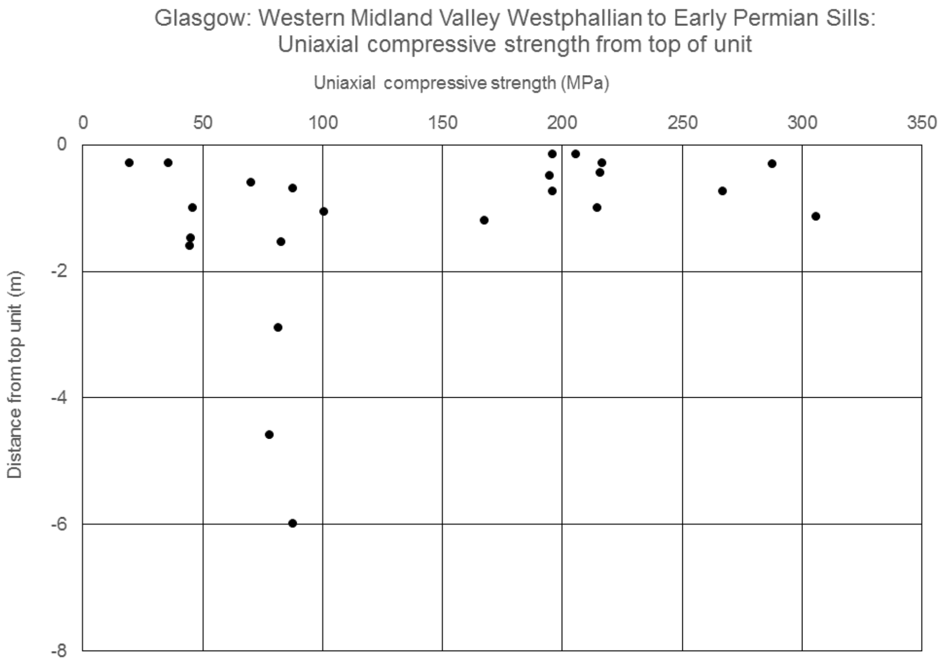

Figure 61. Western Midland Valley Westphalian to early Permian Sills: Uniaxial compressive strength plotted against distance from the top of the unit

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