3D attributed models for addressing environmental and engineering geoscience problems in areas of urban regeneration – a case study in Glasgow, UK.

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Introduction

The City of Glasgow is situated on and around the lower floodplain and inner estuary of the River Clyde (Figure 1) in the west of Scotland, UK. Glasgow's urban hinterland once was one of Europe's leading centres of heavy industry, and of ship building in particular. The industries were originally fed by locally mined coal and ironstone. In common with many European cities, the heavy industries declined and Glasgow was left with a legacy of industrial dereliction, widespread undermining, and extensive vacant and contaminated sites, some the infilled sites of clay pits and sand and gravel workings.

Major regeneration and development is under way in Glasgow. Local and national Government and private developers are investing heavily in areas prioritised for new housing, retail, industry and other infrastructure. These areas include, among others, the waterfront of the River Clyde, and the Clyde Gateway development area of approximately 800 hectares in the eastern part of the city. However, success of these initiatives depends on overcoming key environmental and engineering geoscience problems, including:

- Hazards related to past shallow mine workings (coal, ironstone etc.)
- contamination of land and water (surface and groundwater)
- impacts of flooding
- and potential sea-level change

Therefore, Glasgow's planners and developers need reliable, up-to-date, and immediately accessible environmental and engineering geoscience information and knowledge, to replace that which currently exists (e.g. Browne et al. 1986, Browne and McMillan 1991), about the areas prioritised for regeneration. The British Geological Survey (BGS), in partnership principally with Glasgow City Council (GCC), and with others, is addressing these geoscientific needs through a multidisciplinary and multi-scaled project. The project is assimilating large amounts of geoscientific data to create and deliver attributed 3D models and comprehensive geoscientific databases. The approach taken is not unique to Glasgow, however, as BGS is also currently contributing to sustainable land development through comparable multidisciplinary projects in similar areas of urban regeneration elsewhere in the UK, including the cities of Manchester, Salford and Liverpool in the north-west of England, and London and the Thames Gateway in the south-east of England.

Information Management

BGS holds a wide range of data in over 400 datasets, acquired since 1835. All of the datasets are described by comprehensive discovery metadata (ISO 19115:2003 standard), a subset of which is published on the BGS Internet webpage (http://www.bgs.ac.uk/discoverymetadata/home.html).

The scanning and digitisation of maps and records held in BGS's national archives have paved the way for development of digital products that address the evolving requirements for geoscience data (Culshaw 2005). The large-scale digitisation programmes undertaken in recent years for the Glasgow area by BGS and Glasgow City Council have already greatly increased the availability of data and the capability to share them (Mellon and Frize 2006).

BGS's current work focussing on the catchment of the River Clyde (Figure 1), is drawing heavily on information contained in BGS's archives of borehole information which include records of more than 35,000 boreholes in the Glasgow area alone. Most of these have now been stratigraphically coded, for both superficial deposits and bedrock, to a level appropriate for modelling. In addition, Glasgow City Council has supplied substantial amounts of recently acquired site investigation data from key development sites in the industry standard AGS (Association of Geotechnical and Geoenvironmental Specialists) digital format. The borehole data are supplemented by data from digital maps and mine plans.

3D Models

3D geological models are being systematically developed by BGS under the LithoFrame Project (Kessler and Mathers 2004), which aims to produce geological models for the UK at scales ranging from 1: 1 000 000 to 1: 10 000. BGS has developed systems for corporate data entry, data retrieval and model storage and metadata, and modelling capability and methodology (Smith 2005). Local to regional scale (1: 10 000 – 1: 50 000) detailed models, which focus on characterising the near-surface superficial deposits and shallow bedrock (less than 200m depth) (Kessler et al. 2005), are of most use in urban planning and development, such as in Glasgow. BGS is therefore producing a first generation of local and regional scale digital 3D attributed geological models of the Glasgow area (Merritt et al. 2006), and will extend these across the catchment and inner estuary of the Clyde. These models synthesise the available digital data from boreholes, geological maps, mine plans and terrain models.

The 3D models are then employed to illustrate and interpret:

- the distribution and thickness of superficial deposits and artificial ground
- variations in the complex bedrock geology, including fault locations and displacements, and the extent and depth of known and probable past mine workings, and
- spatial variations in geotechnical, geochemical, hydrogeological and geophysical properties

Uncertainty overlays are also generated for the Glasgow models. Initially, these were based on the density of data used in interpretation, but BGS is now working towards representing model uncertainty to include factors such as geological complexity and data quality.

Modelling Superficial Deposits

BGS uses GSI3D (©Insight GmbH) software to build the models of the shallow subsurface (especially superficial deposits and artificial ground). The software has been developed for BGS to suite its own needs and those of its user community. The GSI3D method utilises a digital terrain model, geological surface outcrops and down-hole coded borehole data to enable the geologist to correlate between boreholes and the outcrops, or subcrops, of geological units, and to construct intersecting cross-sections (fence diagrams). The cross-sections and geological envelopes (limits of the geological surfaces) are used in the GSI3D model calculation by the triangulation method. The GSI3D workflow is shown in Figure 2. Models, attributed with geotechnical, hydrogeological and other properties, are then published in the BGS-owned Lithoframe Viewer. This is an easy-to-use, interactive model-viewing tool in which the user can create synthetic cross-sections, horizontal sections (slices) and boreholes anywhere within the model. This is potentially of considerable value, for example in planning transport routes such as underground railways, in refining development footprints, and in planning site investigations. The attributed 3D geological model is, therefore, a powerful predictive tool and time saving asset that assimilates large amounts of urban geodata into one easy-to-use package. However, it must not be regarded as a substitute for detailed site investigation

Modelling Bedrock

The Carboniferous bedrocks which underlie Glasgow comprise simply folded and complexly faulted strata. Varying data densities of borehole, mine plan and map outcrop points constrain the position of coal seams, stratigraphic boundaries and faults in 3D. With the addition of geologists' interpretive data, the GoCAD™ structural workflow was used to model key shallow coals, stratigraphy and faults (Figure 3). As shallow mineworkings are often an issue for planning and redevelopment, because of the added costs to projects, the faulted coal seam surface models, combined with areas of known and probable areas of mineworkings, provide an improved digital dataset to determine the extent and depth of this hazard.

Applications of the Models

The models are the keys in Glasgow to:

- identifying and investigating problematic ground conditions,
- researching environmental issues, such as the migration of surface contaminants into the groundwater system,
- finding ways to mitigate hazards (e.g. from past mining and contamination), and so
- ensuring that the land is redeveloped in a safe and sustainable fashion for the long-term benefit of the community.

A 3D geological model (for a 25 sq km area) including superficial deposits and key coal seams has already been supplied under evaluatory license to Glasgow City Council in the Lithoframe Viewer for use in planning the redevelopment of the Clyde Gateway area in eastern Glasgow.

Geotechnical Attribution of the Models

The GSI3D models can be attributed on a bulk basis with typical physical properties characteristics, i.e. individual formations/units can be assigned a particular attribute (Figure 4). Synthetic boreholes and synthetic cross sections can then be generated from the variously attributed 3D models, and attributions with respect to variations in depth below ground surface (Figure 5), or any other modelled surface e.g. water surfaces, can be displayed. The models, if used, for example, for planning a site investigation, can be revised subsequently with the addition of new site investigation data to create a ground model of the site.

Although the 3D model provides the relationships between the different modelled units it does not fully present the variation within each unit. This is shown in other ways. In cross-sections, 'borehole sticks' are classified for one or a number of characteristics such as lithology, described strength (Figure 6), detailed permeability or parameters such as standard penetration test N-values. Data are also shown in summary graphs (e.g. box and whisker plots) or depth profile plots for each parameter. However, given the limitations of the 3D software in providing an interactive way of showing data, cross-sections and other information, an engineering geological GIS has also been developed for the Glasgow area. Also being the desired format of local authorities for displaying most geoscientific information, the GIS-compatiblility of outputs from GSI3D is therefore fundamental. Using the GIS, plots of, for example, plasticity, depth parameters, particle size distribution and Excel charts of Standard Penetration Tests and un-drained shear strength can be displayed in relation to the geological surfaces generated during the 3D modelling.

Groundwater Modelling

A new development is linking GSI3D with an existing numerical groundwater flow model, ZOOMQ3D. The ZOOM family of numerical groundwater models consists of the saturated groundwater flow model ZOOMQ3D (Jackson and Spink 2004), an advective transport particle tracking code ZOOPT (Jackson 2004) and a distributed recharge model ZOODRM (Mansour and Hughes 2004). All these models are created using a pre-processor called ZETUP and spatial input files from a GIS (Jackson and Spink 2004). ZOOM was developed using object-oriented techniques, a programming approach commonly applied in commercial software development but only relatively recently adopted in numerical modelling for scientific analysis. The main feature of the ZOOM models is that of grid refinement, so that any number of linked finite-difference grids can be used to zoom in on a particular part of the groundwater system.

An interface between the groundwater flow model ZOOMQ3D and GSI3D has been developed, and is being trialled using the GSI3D models created for Glasgow. A ZOOM grid is defined and set up in the normal way, but the values for the top and bottom of each hydrogeological layer and the hydraulic properties of each layer are exported from GSI3D. A modified version of the pre-processor ZETUP uses these GSI3D data to create ZOOM input files. The whole process is no more difficult than setting up a ZOOM model using a GIS. The development of this new interface and of the ZOOM family of models is continuing, and the experience built up during the trial using the Glasgow GSI3D model will help to improve future versions.

Geochemical Survey

BGS has undertaken extensive geochemical sampling of Clyde tributary stream sediments, stream waters and soils in Glasgow and its peri-urban area. Sediment and water samples have been analysed for approximately 60 organic and inorganic substances to provide an overview of the quality of the urban drainage system and the urban soil quality. Elements of particular concern are chromium, arsenic, cadmium, and lead. Current work aims to integrate these data with hydrogeological datasets to develop a 'first-pass' GIS-based risk assessment tool. This would be intended to determine potential threats to shallow groundwater from the leaching and downward movement of surface contaminants in soils. Integration with similar data from the estuary of the Clyde will provide insight into contaminant migration throughout the Clyde valley and into its estuary.

Estuarine Studies

Shallow geophysical surveys, and chemical analyses of sediments, were undertaken in the inner and outer Clyde Estuary to characterise and identify possible sites of contamination. Boomer, side-scan and multi-beam surveys were used to establish the nature and thickness of the sediment column. Surface and cored sediment samples were then analysed for a wide range of geochemical elements and organic compounds. The initial results show the effect of industry in the estuarine sediments.

Summary

- BGS has developed significant information management and modelling capability leading to the integration of digital geoenvironmental datasets based on attributing and analysing 3D geological models developed with bespoke software.
- In the Glasgow area, work is ongoing to combine digital geological data with that for physical properties, geochemistry and hydrogeology to provide up-to-date and accessible information and knowledge for planners and developers. These products will improve our understanding of surface and groundwater contamination, hazards related to past mining, and impacts of flooding and sea–level change and will assist planners, developers and regulators in making decisions about sustainable land-use and regeneration.

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Figure Captions

Figure 1 Location of Clyde catchment and Glasgow conurbation, with some of the available interdisciplinary digital datasets.

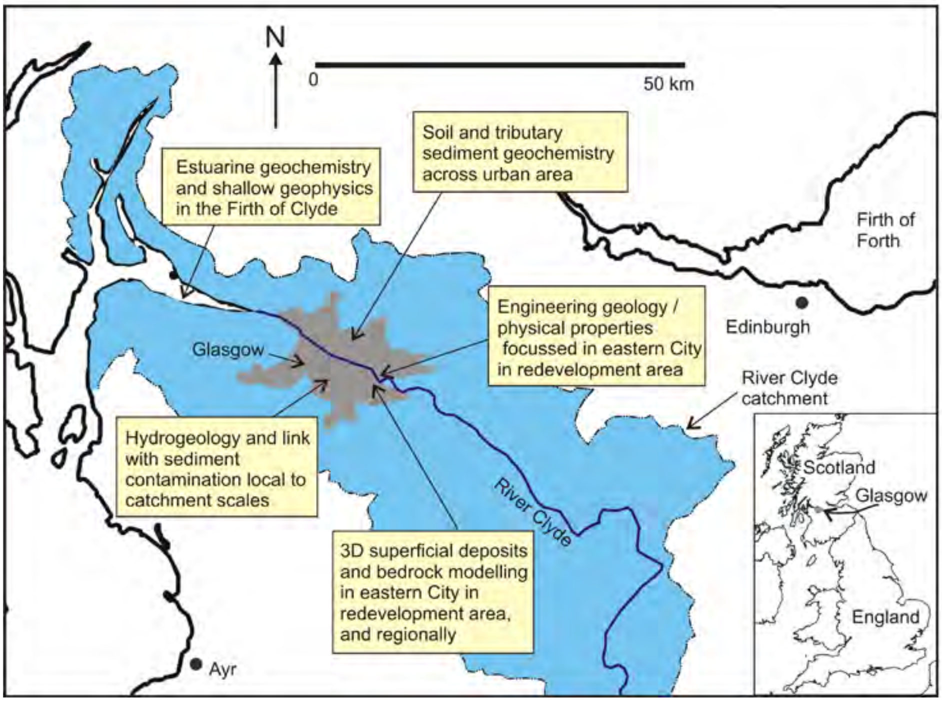
Figure 2 Superficial deposits GSI3D modelling workflow

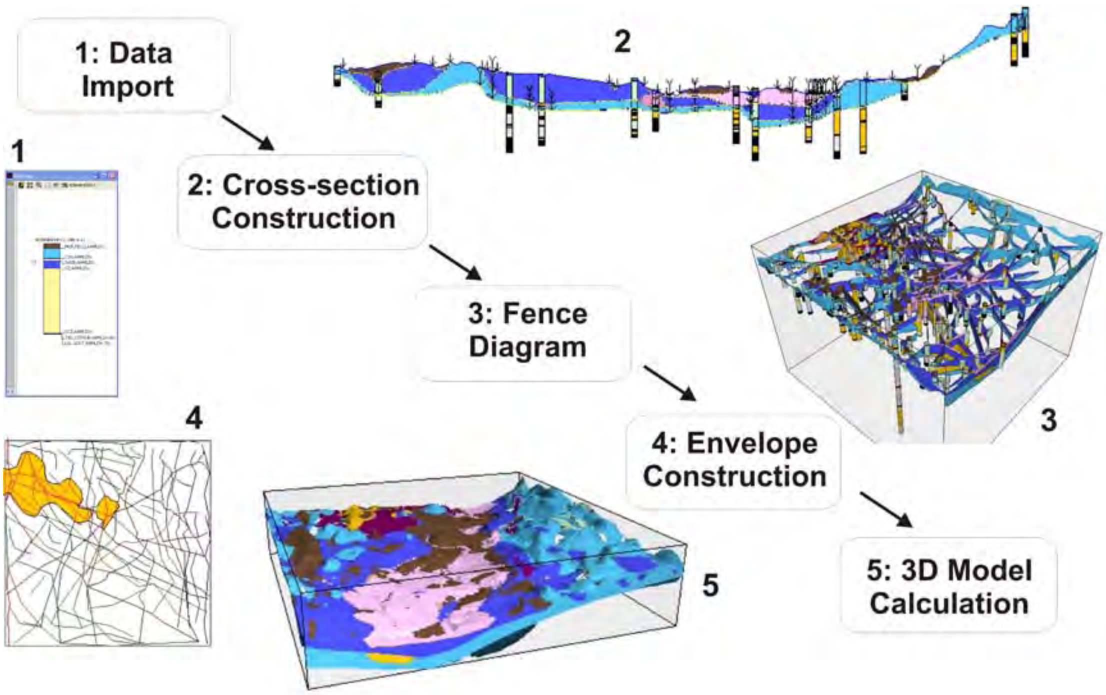
Figure 3 Overview of bedrock model to 200m beneath rockhead for eastern Glasgow comprising two stratigraphic and four coal seam surfaces. Faults in pink (excluding top corner).

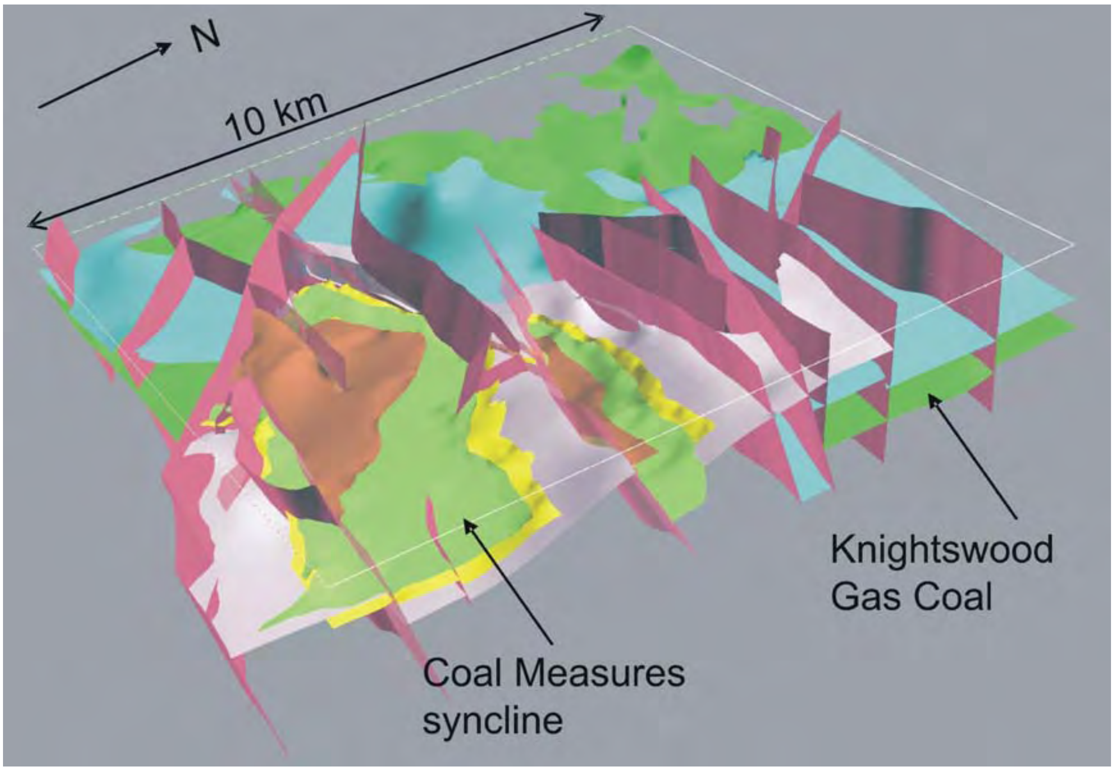
Figure 4 3D model of superficial and artificial deposits from part of eastern Glasgow attributed with engineering geology classification. Bedrock is shown in white.

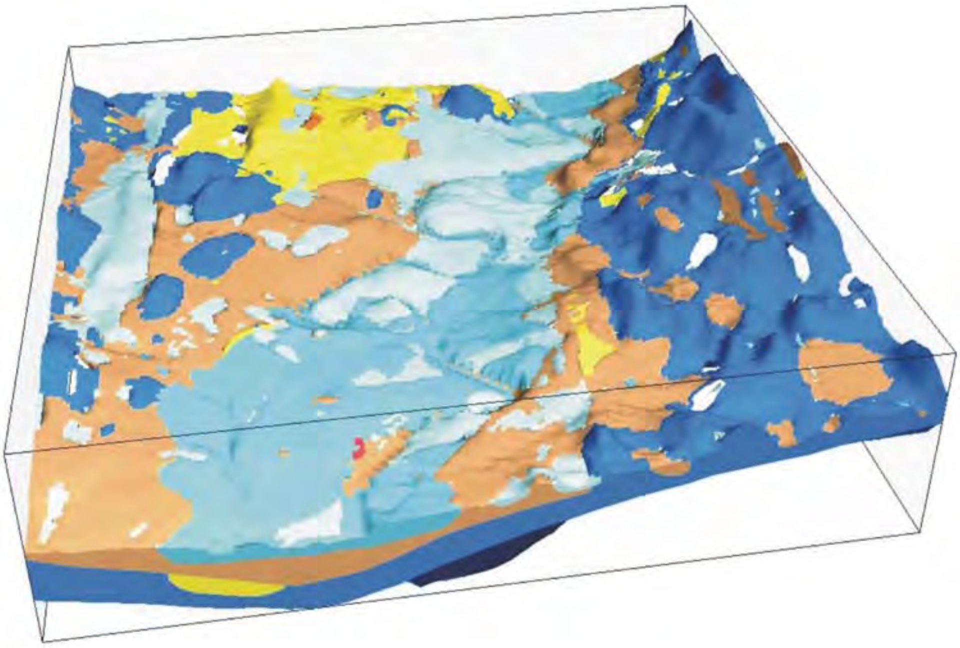
Figure 5 Plan views (slices) of engineering geology classification from the 3D model (Fig 4) at surface, 2 m, 5 m and 10 m below ground surface. Key as for Figure 4. Bedrock is shown in white.

Figure 6 East-west section across part of eastern Glasgow: the cross-section is attributed for lithostratigraphy whereas the 'borehole sticks' are colour coded for described strength/density (left) and rock quality designation (RQD) (right), showing the considerable internal variations in properties of the lithostratigraphic units.


N
0
50 km
Soil and tributary sediment geochemistry across urban area
Estuarine geochemistry and shallow geophysics in the Firth of Clyde
Firth of Forth
Engineering geology / physical properties focussed in eastern City in redevelopment area
Edinburgh
Glasgow
River Clyde catchment
Hydrogeology and link with sediment contamination local to catchment scales
Scotland
Glasgow
River Clyde
3D superficial deposits and bedrock modelling in eastern City in redevelopment area, and regionally
England
Ayr


1: Data Import
2
1
2: Cross-section Construction
3: Fence Diagram
4
3
4: Envelope Construction
5
5: 3D Model Calculation



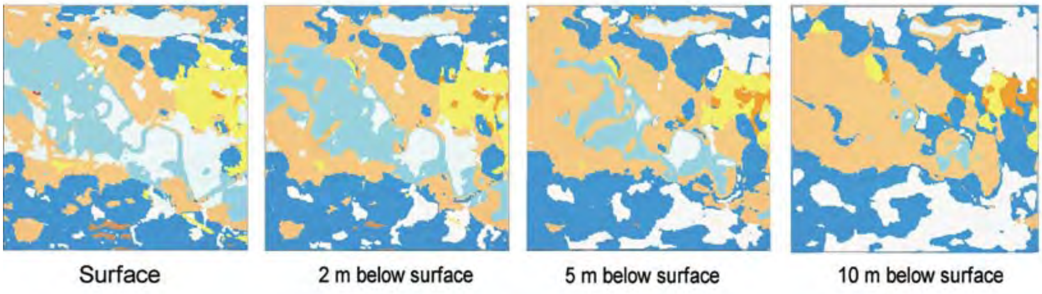


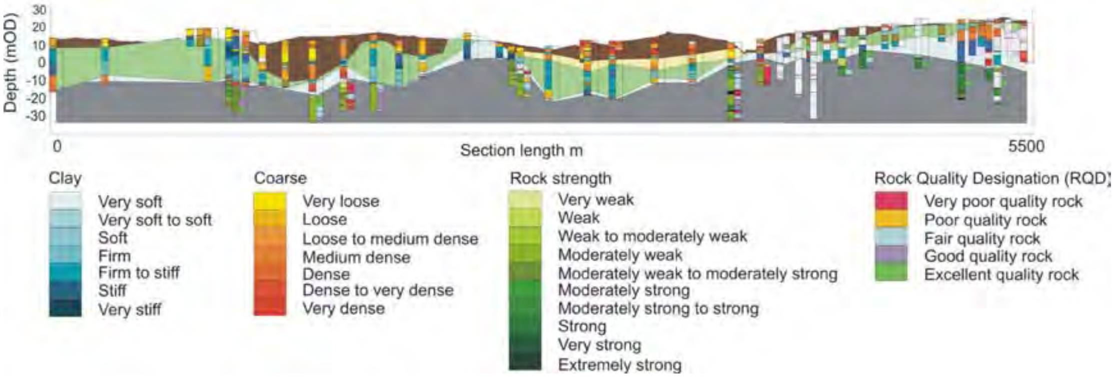
Organic Soil
- Peat

Mixed fine- and coarse-grained
- Very soft to very stiff/loose to very dense: Made Ground
- Very soft to very stiff/loose medium dense CLAY or SILT, SAND or GRAVEL: Law and Gourock Formations
- Firm to stiff/dense very dense gravelly sandy CLAY or SAND and GRAVEL: Wilderness Formation

Mostly fine grained
- Very soft to firm/(loose) laminated (sand) SILT and CLAY: Paisley Formation
- Firm to stiff laminated SILT and CLAY: Bellshill and Broomhouse (fine grained) Formations

Coarse-grained
- Loose to medium dense silt SAND and SAND: Bridgeton, Ross and Killearn Formations
- Medium to very dense silty gravelly SAND and/or GRAVEL: Broomhouse Formation


Surface
2 m below surface
5 m below surface
10 m below surface


Depth (mOD)
30
20
10
0
-10
-20
-30
0
Section length m
5500
Clay
Very soft
Very soft to soft
Soft
Firm
Firm to stiff
Stiff
Very stiff
Coarse
Very loose
Loose
Loose to medium dense
Medium dense
Dense
Dense to very dense
Very dense
Rock strength
Very weak
Weak
Weak to moderately weak
Moderately weak
Moderately weak to moderately strong
Moderately strong
Moderately strong to strong
Strong
Very strong
Extremely strong
Rock Quality Designation (RQD)
Very poor quality rock
Poor quality rock
Fair quality rock
Good quality rock
Excellent quality rock