A tribute to Professor William Dearman: new small-scale engineering geological maps of the United Kingdom

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ABSTRACT: Professor William Robert ("Bill") Dearman was the first British Professor of Engineering Geology and a world leader in the development of engineering geological mapping techniques and methodologies, recognised by being awarded the IAEG's Hans Cloos Medal. The maps described here would not have been completed without his initial ideas and interpretative work. It is a great regret that the maps were not finished in time for him to see them before his death in January 2009. This paper and the maps described in it are, therefore, dedicated to his memory.

In 1996-7, the British Geological Survey (BGS) collaborated with Professor Bill Dearman to develop a small-scale engineering geological map of the United Kingdom (UK). Professor Dearman developed the methodology, first outlined in his 1982 paper with Eyles on an engineering geological map of the UK, using geological map information at 1:625 000 and 1:250 000 scales. The map was intended to have an extensive legend and a series of text boxes, block diagrams and sections that explained geological processes relevant to development and remediation. The initial interpretation was completed but, unfortunately, the map was never published. In late 2008 it was decided to revive the original interpretation and to apply it to a new digital version of the 1:625,000 scale geological map. Two engineering geological maps have been produced, for bedrock and for superficial deposits. Professor Dearman's methodology has been adapted, by varying degrees, for the two maps. This paper briefly describes the methodology adopted. The original igneous, sedimentary and metamorphic bedrock classification methodology has been revised to better reconcile the classes to modern geological and engineering geological interpretations and classification systems. Mainly, this has involved the reinterpretation of classes within the metamorphic and igneous groups and some reinterpretations and additions to the mudstone, sandstone and limestone classes within the sedimentary group. The original superficial deposits classification methodology has been found to be largely compatible with modern geological and engineering geological interpretations and classification systems and so has been left largely un-amended apart from the addition of a number of sub-divisions of 'Glacial Till.'

1 INTRODUCTION

Professor William Robert ('Bill') Dearman (Fig. 1) was the first British Professor of Engineering Geology. He played a significant role in the development of the subject in construction and land-use planning in the UK, as well as leading world-class research into engineering geological mapping (Reeves 2008). In 1970 Professor Dearman represented the UK interest at the first meeting of the International Association of Engineering Geology (now the International Association for Engineering Geology and the Environment [IAEG]) Commission on Engineering Geological Mapping, held at the first IAEG Congress in Paris. As part of the Commission's work, the 'UNESCO Guide to the Preparation of Engineering Geological Maps' was produced (Anon 1976). This was preceded by a report from the UK Geological Society's Engineering Group Working Party on 'The Preparation of Maps and Plans in terms of Engineering Geology' (Anon 1972), much of which was incorporated in the UNESCO guide. This was the first publication in the UK to encompass the description of soils and rocks in 'engineering' terms, and was the pre-

cursor to the revised British Standard Code of Practice for Site Investigations (Anon 1981, later revised as Anon 1999).
Professor Dearman's work and contributions to such publications have helped to demonstrate the principles and importance of engineering geological mapping within any major ground investigation project (Reeves 2008). This was also evident in his contributions and dedication to the international engineering geological community, especially through his editorial and committee work for the IAEG, which helped to raise the profile of the importance of engineering geology and was recognised by him being awarded the IAEG's Hans Cloos medal in 1990 and the Geological Society of London's William Smith medal in 1991.

Figure 1. One of the last photographs taken of Professor Bill Dearman

Sadly, Professor Dearman died on the 6th January 2009 before this paper and the maps described in it were completed. Therefore, the authors would like to dedicate the paper and the maps to his memory and to celebrate his achievements.

One of Professor Dearman's most significant publications was his book on 'Engineering Geological Mapping' (Dearman 1991). Now, with technological advances in the last two decades, the spatial representation of engineering geology that he described has evolved from paper-based 2D maps (Dearman 1991) to 2.5D digital maps in a geographical information system (GIS) environment (for example, Culshaw & Ellison 2002) and on to true 3D digital maps/models (Culshaw 2005, Kessler et al. 2008, 2009). At the same time, the rather prescriptive methodologies for the preparation of engineering geological maps, as developed by the Engineering Group of the Geological Society in the UK (Anon. 1972) and the IAEG (Anon 1976), have fallen largely into disuse.

New developments in engineering geological mapping and modeling (in the broadest sense) have mostly been at large (1:10,000 and greater) and medium scale (< 1:10,000 and > 1:100,000). While small-scale national engineering geological maps were quite commonly produced in the 1960s and 1970s, for example, for Slovakia (at 1:500,000 scale) (Matula 1969), for the USA at 1:7,500,000 scale (Radbruch-Hall et al. 1979), and the UK originally at 1:2,000,000 but published at approximately 1:4,350,000 scale (Dearman 1991 but based on earlier work), few have been produced in the last twenty five years. This is perhaps not surprising as the maps that were produced were created mostly to test methodologies and show what could be done rather than to have any specific practical application.
This paper discusses the newly-completed small-scale engineering geological maps of the UK. The methodology used is explained and the rationale for developing the maps, at all, is presented.

2 METHODOLOGY

2.1 *Professor Dearman's legacy (the 1996-1997 engineering geological map)*

While the original 1996 - 97 engineering geological map was not published, all the interpretative work that had been undertaken by Professor Dearman was retained by the BGS. The legacy was substantial. Professor Dearman had determined the engineering geological lithologies for both bedrock and superficial deposits, combined engineering geological lithologies using a system of stripes to create engineering geological map units, completed the geotechnical interpretation of the bedrock lithostratigraphy, largely completed the geotechnical interpretation of the superficial deposits lithostratigraphy and had drafted a key, which included detailed information on engineering considerations associated with each engineering geological lithology. In addition, a series of inset maps, text boxes and block diagrams had been agreed for inclusion with the map.

2.2 *Base maps and line-work*

The 1996 - 97 engineering geological map was based on the BGS 1:625,000 scale bedrock (3rd edition) and superficial geology (1st edition) maps of the UK (Anon. 1977a, b; 1979 a, b). Professor Dearman began compiling the engineering geological map by tracing the lithostratigraphical boundaries of the BGS superficial and bedrock maps onto two separate sheets, one for bedrock deposits and one for superficial deposits. This allowed each 'blank' lithostratigraphical polygon to be re-attributed, by hand, with an engineering geological map unit.

The finalised engineering geology maps produced by the BGS in 2010 are based on the 5th edition of the BGS 1:625,000 scale bedrock geology map (Anon. 2007a, b) and the recently compiled line-work for a new superficial geology map of the UK. The line-work had been substantially updated since the previous editions of the two maps, taking into account recent field mapping as well as changes to the lithostratigraphy created by the introduction of new formations and groups. Both maps were produced digitally, thereby allowing the drafting of the 2010 engineering geological maps to be undertaken within a GIS.

2.3 *Engineering geological lithologies and engineering geological mapping units*

The engineering geological lithologies used by Professor Dearman for the 1996 - 97 map were a revision of the classes used on an earlier 1:2,000,000 scale Engineering Geological Map of the United Kingdom (Dearman & Eyles 1982), which, themselves, were adopted from a simplified geology map (Bickmore & Shaw 1963). These lithologies were then combined in varying proportions to create an engineering geological map unit, using the same methodology as for the 1:2,000,000 scale Dearman & Eyles Map.

These engineering geological lithologies, while appropriate at the time, needed updating to better reconcile the descriptions with modern interpretations and standards for engineering geology, particularly those used by the BGS (Gillespie & Styles 1999, Hallsworth & Knox 1999, Robertson 1999) and found within the current British Standard for site investigation (Anon. 1999). The engineering geological lithologies used for 1996 - 97 and the 2010 map are compared in Table 1.

Relatively few changes have been made to the superficial deposits engineering geological lithologies. The 2010 subdivision has been made primarily on grain size and organic content. However, 'Glacial Till,' a genetic term, is included. The classes 'Alluvium' and 'Clay-With-Flints' proposed by Professor Dearman are not in keeping with this approach, as they are lithostratigraphical descriptions rather than engineering descriptions. The use of the term 'Glacial Till' is also a departure from this methodology, but its inclusion is considered justified by the use of additional qualifiers and because the term has strength connotations.

The current draft 1:650 000 scale superficial geology map (Fig. 3) presents all the glacial till deposits as a single unit as did the original map. Recent work has separated the glacial tills into groups, sub-groups, formations and, in some cases, members. The groups are based on age (Anglian or Devensian glaciation); sub-groups contain formations and lithogenetic units of similar lithology and provenance. Formational status is assigned to regionally significant mappable areas based on lithology and physical characteristics, accepting lateral and vertical variation is likely. Discontinuous mappable units such as interbeds may be assigned member status (McMillan et al. 2004).

The engineering geological classes of the glacial tills reflect the primary lithological type (that is, fine- or coarse-grained), engineering characteristics, (that is, stiff or dense) and secondary characteristics that are of engineering importance. These include layered, coarse-grained beds and laminated clay and silt beds, which may, for instance, produce slope stability problems in cuts (Hughes et al. 1998) and the presence of strong boulders or rafts, which will impact on drilling and tunneling.

Significant changes were made to the sedimentary bedrock engineering geological lithologies. The 2010 subdivision has again been made principally on the basis of grain size and chemistry but also on strength. The term 'Shale' has been removed as it is only recognised in the context of organic rich sediments and rocks by the BGS (Hallsworth & Knox 1999) and is not in the British Standard for site investigation (Anon. 1999) (though it is in the International Standard [Anon. 2003]). Sandstone has been separated from conglomerate as the two lithologies have different engineering behaviour. In addition, further classes, such as 'Strong Limestone' and 'Strong Chalk,' have been added to account for the differences in geotechnical properties and engineering behaviour, which arise as a result of variations in strength (Fig. 2). In the case of chalk, the variation in strength is clearly discernible geographically: those of the White Chalk Subgroup in the Southern Province being significantly weaker than those of the Northern Province in Lincolnshire and Yorkshire in eastern England and the Ulster White Limestone Group in Northern Ireland (Bell et al. 1999). The class 'Very stiff clay/very weak mudstone' also has been introduced to address the particular engineering considerations that arise from clay-rich sediments that are at the boundary between very stiff or hard soils and extremely and very weak rocks. A similar class was not introduced for 'Sandstone' as the transition from soil to rock within clay-rich rock is often gradational while the transition within sandstone is often more abrupt (partly due to cementation) with sand and sandstone occurring as interbeds, particularly within the Cretaceous. It also was deemed important to indicate the presence of coal-bearing rocks due to the significant engineering implications associated with coal mining in the UK.
Some significant revision has been made to the metamorphic rocks classes, once more based on accepted standards within the BGS. The classification of metamorphic rocks is somewhat unclear and imprecise and, in the authors' experience, does not appear to have been well addressed in engineering geological classifications generally. It was decided that the most appropriate subdivision of metamorphic rocks for engineering purposes would be based on texture, and so the BGS root classification names, which are based on texture, were used (Gillespie & Styles 1999). These terms would be both more recognisable and more appropriate than descriptions based on mineral composition, such as pelite and psammite, currently favoured by the BGS. The only term not used within the British Standard, and so possibly unfamiliar to UK engineering geologists, is 'Granofels.' The use of 'Granofels' is justified as it is the only word that unambiguously describes a non-foliated, fine to coarse grained metamorphic rock (for example, quartzite). The two terms used that are a departure from the BGS textural root classification names are 'Mylonite' and 'Marble.' These terms have been added to account for significant differences in engineering behaviour which arise as a result of foliation, grain size, genetic origin, mineralogy and weathering. 'Mylonite' is used for an intensely-deformed, fine-grained rock found within large fault complexes. 'Marble' is used for a metamorphic rock containing > 50 % by volume of carbonate minerals. The term 'Greywacke' was removed as, technically, it is not a sedimentary rock and is not a term commonly used in engineering geology. Rocks described by Professor Dearman as 'Greywacke' in the 1996 - 97 map have been classified as 'Strong Sandstone' in the 2010 map (Fig. 2).

The subdivision of the igneous classes has been made on the basis of mineral chemistry and grain size. While the 2010 map (Fig. 2) classes appear very similar to Professor Dearman’s, that is, the replacement of the class 'Basalt' with 'Basaltic-rocks,' it was felt that this distinction was necessary to indicate that the class includes other fine-grained mafic rocks, in addition to basalt, such as andesite and phonolite. Medium-grained, igneous rocks were not classified separately from coarse-grained ones as their engineering behaviour with respect to strength and jointing is similar. It is worth noting that no separate class has been created for volcaniclastic rocks. They are commonly interbedded within other extrusive volcanic rocks. In the case of 'Basaltic rocks,' the occurrence is considered relatively minor and not to have a significant impact upon the engineering considerations. Tuffs and ignimbrites are important rock types in some areas. Their behaviour is considered to be similar to the fine-grained felsic rocks they are associated with and so they have been included within the 'Rhyolitic rocks' class.

2.4 *Engineering geological interpretation*

Professor Dearman attributed the 1996 - 97 map with engineering geological map units based upon interpretation of BGS lithostratigraphical groups and his own considerable knowledge. The relative proportions of engineering geological lithologies within each mapped unit were determined by reviewing stratigraphic columns on the BGS 1:50,000 scale bedrock maps and from descriptions contained within BGS local and regional geological memoirs. So, for example, the Cretaceous Hastings Beds, which consist of interbedded sands and clays became 'Fine Soil' and 'Coarse Soil' in the proportion 1:1, represented on the map as alternating, coloured stripes of equal width; the separate colours representing each engineering geological lithology.
As with Professor Dearman’s 1996 - 97 engineering geological map, the principle of applying an engineering geological interpretation to the pre-existing lithostratigraphical classes was adopted for the 2010 maps (Fig. 2 & 3). In practice, the re-attribution of polygons was achieved by adding a new field to the existing geological layer attribute table (in the GIS) and populating this field with the new engineering geological unit. So, for example, all GIS polygons attributed with 'Tappins Group' (a Lower Palaeozoic sedimentary sequence found in southern Scotland) in the lithostratigraphical description field were selected and the engineering geological map field updated with 'Strong Sandstone and Slate (in the proportion) 1:1.' In this way, over 11,000 polygons within the bedrock map and over 13,000 polygons within the superficial map could have an engineering geological map unit description added almost en masse. Using a GIS as the basis for the engineering geological maps has meant that the drafting of the map has been simply a matter of re-colouring the latest editions of the bedrock and superficial maps using the engineering geological map unit description field rather than the lithostratigraphical description field (Fig. 2 & 3). This is a relatively simple and rapid process, which is easily updated and edited - a far cry from the hand-drafting undertaken by Professor Dearman for the earlier map!

A number of sources were consulted to ‘translate’ the lithostratigraphical groups and formations into engineering geological map units. Information on grain size and chemistry was obtained from lithological descriptions found on BGS 1:50,000 scale geological maps, BGS regional and local memoirs, the BGS Lexicon (Anon. 2010) and Professor Dearman’s 1996 - 97 Map. Information on the strength of lithostratigraphical groups and formations was obtained from Reeves et al. (2006), the BGS National Geotechnical Properties Database (Self & Entwisle 2006), research to develop strength and density maps of Great Britain (Busby et al. 2009) and on assumptions based on lithostratigraphical boundaries. For instance, all sandstones and limestones of the Carboniferous Period or older are assumed to be strong. The differentiation between mudstone and slate is based on metamorphic zones.

Table 1 – Comparison of engineering geological lithologies.

Dearman's 1996-97 map	2010 Map
Superficial Deposits Engineering Geological Lithologies	
Fine soil	Fine soil
Coarse soil	Coarse soil
	Fine to coarse soil
Organic	Organic soil
Glacial till	Fine till
	Fine till (bouldery)
	Fine till (layered)
	Coarse till
	Coarse till (layered)
Alluvium	
Clay-with-flints	
Sedimentary Bedrock Engineering Geological Lithologies	
Fine soil	Fine soil
Coarse soil	Coarse soil
Mudstone and shale	Very stiff fine soil/weak mudstone
	Mudstone
Sandstone and conglomerate	Sandstone
	Strong sandstone
	Conglomerate/breccia
Oolitic limestone	Oolitic limestone
Limestone	Limestone
	Strong limestone
Chalk	Chalk
	Strong chalk
Metamorphic Bedrock Engineering Geological Lithologies	
Slate	Slate
Slate and greywacke	
Schist	Schist
Gneiss	Gneiss
Quartzite	
Limestone	Marble
	Granofels
	Mylonite
Igneous Bedrock Engineering Geological Lithologies	
Basalt	Basaltic-rocks
Rhyolite	Rhyolitic-rocks
Gabbro	Gabbroic-rocks
Granite	Granitic-rocks

2.5 *The key and legend*

The bedrock and superficial engineering geological maps each has a legend that defines the coloured polygons on the map face in terms of the engineering geological lithologies and their proportions (if necessary). In total, the 2010 bedrock map includes 22 engineering geological lithology classes, represented within 68 engineering geological map units (there are more units because lithologies are combined in different proportions). These have replaced 243 lithostratigraphic classes. On the superficial deposits map, 9 engineering geological lithology classes and 9 engineering geological map units replace 14 lithostratigraphic classes (Fig. 2 & 3). The original key, compiled by Professor Dearman, included a description of each engineering geological lithology and information on engineering geological considerations, including suitability for foundations, excavatability, use of material as engineered fill, and appropriate site investigation approaches. The classes shown on the key were based on those used for an engineering geological map (compiled by one of the authors - KJN) produced to provide information to civil engineers and planners in the Bradford area of West Yorkshire in northern England (Waters et al. 1996). An example of the part of the key for 'Strong Sandstone' is shown in Table 2.

Table 2. Extract of the map key for the engineering lithology 'Strong Sandstone.'

DESCRIPTION	FOUNDATIONS	EXCAVATION	ENGINEERED FILL	SITE INVESTIGATION
Moderately strong to extremely strong, medium to widely jointed, thinly to thickly bedded, fine to coarse grained SANDSTONE; may contain slate or mudstone and siltstone beds. Weathers to a loose to very dense sand, gravel or silty/clayey sand. Low to high permeability; flow is through matrix and discontinuities. Includes ‘Greywacke.’	Usually very good foundation conditions, depending on the nature and thickness of the weathered zone.	Highly weathered rock may be diggable. In fresher material ripping, pneumatic tools or blasting is required depending upon joint/bedding spacing and orientation. Where fresh or slightly weathered, excavated slopes may maintain long-term stability.	Suitable as high grade granular/rockfill if care is taken in selection and abstraction.	Important to determine intact rock strength, spacing, orientation and nature of discontinuities (including water flows) and nature/depth of weathered zone materials.

The descriptions in the key follow the format of those for soils and rocks as given in the international standards BS EN ISO 14688-1 (Anon. 2002) and 14689-1 (Anon. 2003) respectively, and summarised in Anon (1999). Several sources were consulted to help compile the key. Information regarding permeability was obtained from (Bell et al. 1986). The criteria for material re-use are based on those of the UK’s Highways Agency specification (Anon. 2005a). Information regarding excavatability, foundation conditions and site investigation was obtained from Professor Dearman’s original work and from the experience of the authors.

2.6 *Inset maps and text boxes*

The faces of the maps include a number of very small scale inset maps, text boxes and schematic diagrams. The purpose of these is to illustrate aspects of the engineering geology that have a significant impact upon land-use and development but could not be incorporated into the main map. The original inset maps and text boxes agreed for the 1996 - 97 map have been changed significantly, both as a result of the decision to split the engineering geological map into bedrock and superficial deposits versions and because of the development of the BGS's 'GeoSure' national geohazard dataset and other datasets and thematic geological maps created by the BGS since 1997 (Walsby 2007, 2008).

Six inset maps are included on the bedrock engineering geology maps. These show structural complexity (after Dearman & Eyles 1982), earthquake epicentres, magnitude and intensity (from BGS databases), shrink-swell susceptibility of clays and mudstones (based on GeoSure data), extent of mining and dissolution susceptibility (based on GeoSure data), sulphate potential (based on research by Forster et al. 1995 and Anon. 2005b) and bedrock permeability (based on Bell et al. [1986] and GeoSure data). On the engineering geology of superficial deposits map three inset maps are included showing landslide distribution and susceptibility (based on the BGS database National Landslide Database [Foster et al. 2008] and GeoSure data), Quaternary domains and ice sheet limits (from BGS databases) and thickness of superficial deposits. The engineering geology of superficial deposits map also includes a number of generic cross-sections showing associations of glacial and alluvial deposits (based on Booth et al. 2010), block diagrams showing landslide types (after Waters et al. 1996), sinkhole types (after Waltham et al. 2005) and types of artificial deposits (after Waters et al. 1996).

Both maps include an introductory text box defining the nature of engineering geology and purpose of the maps. The bedrock engineering geology map has additional text boxes covering faults and shear surfaces, weathering and seismicity. The engineering geology of superficial deposits map contains texts on 'head' and associated shear surfaces and artificial deposits.

3 PURPOSE OF THE MAPS

Radbruch-Hall et al. (1979) suggested that a national scale engineering geological map could be used for the initial planning of major infrastructure programmes, whilst Matula's map of Slovakia and Dearman's maps of the UK (see above) seem to have been produced to show how mapping methodologies should be applied. In an age when digital systems allow a wide range of 2D, 2.5D and 3D maps and models to be professionally produced with comparative ease and generalised maps serving several purposes are unlikely to meet the needs of a specific user, the preparation of a national engineering geological map of the UK seems, at first glance, to be a dated concept.

In recognition of this, the maps described above were produced with a different audience in mind. Almost by definition, school and university students of geology, engineering geology, geotechnical engineering and civil engineering generally have less knowledge and experience of the engineering geological conditions of the country in which they are studying than those who have had experience of research or practice. In the UK, at least, the number of geology/geoscience/earth science departments has reduced over the last twenty five years. Engineering geology has a very weak academic base and geology is taught less to civil engineering students than previously. In the USA, for example, between 1975 and 2000 changes in the requirement for the inclusion of engineering geology in the civil engineering curriculum meant that by the end of the period only 4 % of courses still taught it (Rogers 2002). It is suggested here, that there is a need to remind students at undergraduate and postgraduate levels of the aspects of the national geology that are relevant to a country's physical development and regeneration. One way of doing this is by means of poster maps that present a synopsis of the national engineering geological conditions.

With this objective in mind, it is planned that the two engineering geological maps (Fig. 2 & 3) of the UK, described above, be made freely available to all engineering geology and geotechnical engineering students. It is hoped that the maps will be used by undergraduates and postgraduates mainly from geoscience, civil engineering and environmental sciences. Probably, this will be in the form of a digital file that can be printed at the original scale (1:1,000,000) or smaller. In addition, paper copies will be made available to geoscience and civil engineering departments, and to consultants, contractors and other professional organisations, so that the maps can be hung in laboratories, common rooms and offices. In this way, engineering geology will be brought to the attention of students and less experienced professionals on a regular basis.

4 CONCLUSIONS

The completion of new digital line-work for the British Geological Survey's 1:625,000 scale bedrock and superficial geology maps of the UK in 2009 - 10 provided an impetus for the publication of engineering geological maps of the country at a scale of 1:1,000,000 (Fig. 2 & 3). In 1996 - 97, much of the interpretative work for these maps had been completed by the late Professor Bill Dearman, working with two of the authors. However, changes in priority at the BGS in 1997 prevented publication. The new digital line-work enabled easy re-attribution of the original lithostratigraphical polygons in terms of engineering geological lithology. As well as a map legend, each map includes a key that provides a description of each engineering geological lithology and comments on suitability for foundations, excavatability, use as engineered fill and site investigation priorities. Text boxes that define engineering geology and explain the significance of faulting and of weathering, very small scale inset maps that show structural domains and the distribution of geohazards and some schematic diagrams showing lithological associations with depth for some of the superficial deposits have been included.

The maps are intended to be used mainly by geoscience, civil engineering and environmental science undergraduate and postgraduate students to aid understanding of the importance of geology to development and regeneration. The maps may also be useful to those engineering and environmental geologists and geotechnical engineers in the early stages of their careers who may not be familiar with the geology of the whole of the UK. It is intended that the maps should be made freely available as digital files and that printed versions should be provided to university departments and consultants/contractors and others to display in places of study and work.

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Figure 2. Engineering Geological Bedrock Map of the UK at 1:1 000 000

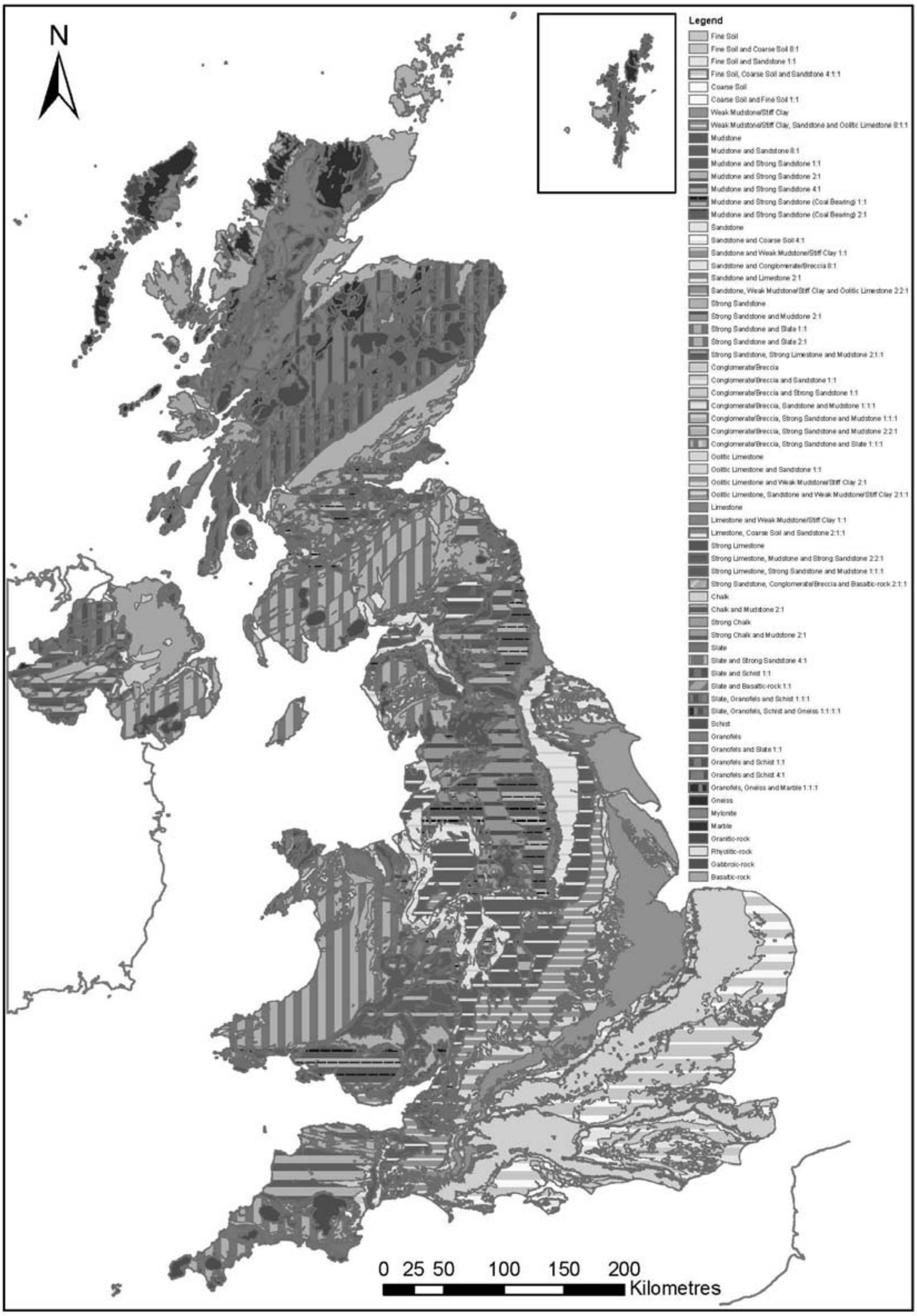

Figure 3. Engineering Geological Superficial Map of the UK at 1:1 000 000