Methodology for creating national engineering geological maps of the UK

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Abstract: In the United Kingdom (UK) geological maps traditionally have been attributed with lithostratigraphical map units. However, without significant supplementary information, these maps can be only of limited use for planning and engineering works. During the middle part of the 20th century, as development of the science of engineering geology began to accelerate, engineering geological maps started to appear in various forms and at various scales to meet the challenge of making geological maps more suited to land-use planning, engineering design, building, construction and maintenance. Today, engineering geological maps are routinely used at various scales as part of the engineering planning, design and construction process. However, until recently there had been no comprehensive, readily available engineering geological map of the UK to provide the broad context for ground investigation. This paper describes the recently published (2011) 1:1 000 000 scale engineering geology superficial and bedrock maps of the UK. It describes the methodologies adopted for their creation and outlines their potential uses, limitations and future applications.

Introduction

By the start of the nineteenth century, William Smith had already produced what is now recognized as 'the first true geological map' (Dearman & Fookes 1974; Forster & Reeves 2008). However, in 1801, Smith had also written a prospectus for a book and map that were intended, in part, to allow canal engineers to take the geology properly into account during design and construction (Sheppard 1917). Unfortunately, the book and map were never published, although parts appeared in a number of Smith's other publications. Although the relevance of geology to building and construction was obvious to many civil engineers and geologists, engineering geological maps, as opposed to geological maps made specifically for an engineering activity, were almost unknown until the end of the nineteenth century (Culshaw 2004a). The First World War saw military engineers use them extensively for military purpose such as the excavation of military dugouts (Rose & Rosenbaum 2011). However, after that war, the development of engineering geological maps was limited mainly to countries such as Germany, Poland, the USSR and Czechoslovakia (Dearman 1991). There was a further revival in the use of geological maps by the British Forces in the Second World War; for example, in preparation for the D-Day landings in Normandy (Rose et al. 2006). In the UK, engineering geological mapping only really came to the fore in the 1970s, when basic methods and techniques for their production were first outlined by the Engineering Group of the Geological Society's Working Party on Preparation of Maps and Plans in Terms of Engineering Geology (Anonymous 1972) and by the International Association of Engineering Geology's Engineering Geological Maps: A Guide to their Preparation (Anonymous 1976). Following this, Dearman (1991) also provided a comprehensive history of engineering geological mapping in his book on the subject.

Anonymous (1976) classified engineering geological maps by scale as well as by purpose and content; large-scale maps were at 1:10 000 or greater, medium-scale maps were less than 1:10 000 and greater than 1:100 000, and small-scale maps were 1:100 000 and less. Small-scale engineering geological maps covering whole countries or regions of large countries are not easily available and little is published on this type of map. Radbruch-Hall et al. (1979) discussed the engineering geological map of the USA, at a scale of 1:7 500 000. Three maps were produced: a geological base map that also showed geological conditions that might affect construction, a geohazard map, and a map showing areas where development or construction might worsen geohazards or detrimentally affect the environment. These three maps were reproduced in monochrome at a scale of about 1:21 000 000 by Radbruch-Hall et al. In the USSR, an engineering geological map at a scale of 1:2 500 000 was produced (Churinov 1972). For a country closer to the size of the UK, Matula (1969) produced a summary engineering geological map of Slovakia at a scale of 1:500 000. This map and that of the USA have been described in more detail by Dearman (1991). In Poland an engineering geological map at a scale of 1:500 000 was produced in 1967, and also in other Eastern European countries at around the same time as part of a co-ordinated project (Kabel 1968).

The first small-scale engineering geological map of the UK was produced by Dearman & Eyles (1982) at a scale of 1:2 000 000, but reproduced in print at a scale of approximately 1:4 350 000 (Dearman & Eyles 1982). This map was based on a simplified geological map of the British Isles within the Clarendon Atlas (Bickmore & Shaw, 1963) and comprised 16 distinct lithology types. Single engineering geological units shown on the map consisted of between one and three of these lithologies in varying proportions, represented by a system of stripes of varying thickness. This resulted in a stripe system that differentiated 11 proportions of the up to three lithological types (Dearman 1991).

The first published engineering geological map produced by a geological survey in the UK was of Belfast at a scale of 1:21 120 (3 inches to 1 mile) (Bazley 1971). Several medium-scale (1:25 000 and 1:50 000) engineering geological maps were produced by the British Geological Survey (see Culshaw & Price 2011) and a range of others were produced for selected urban development areas; for example, Bradford, Bath, NE Wales and Wigan (Forster *et al*. 1987, 2004; Waters *et al*. 1996; Culshaw 2004*b*) as part of a research programme funded and managed by those government departments responsible for land-use planning (Culshaw *et al*. 1988; Smith & Ellison 1999).

Within the BGS a renewed interest in the production of smallscale geological maps to provide summary geological information at a national scale resulted in a collaboration with Professor Bill Dearman between 1996 and 1997 to compile 1:1 000 000 scale engineering geological maps of the UK. Dearman used the BGS 1:625 000 scale lithostratigraphical maps (superficial and bedrock; Anonymous 1977*a*,*b*, 1979*a*,*b*) as a framework from which to work. He reinterpreted the geology and replaced the lithostratigraphical map units with engineering geological map units. It was originally proposed that two maps would be produced; the first would be a map combining superficial and bedrock engineering geology (similar to the map of Dearman & Eyles (1982), reproduced by Dearman (1991)). The methods developed by Dearman and his BGS collaborators Kevin Northmore and Martin Culshaw have been briefly discussed by Culshaw *et al*. (2010). It later became clear that this combined map would be too complicated and would conceal too much of the bedrock beneath superficial deposits. The second map was intended to show the extent of and susceptibility to geological hazards. Unfortunately, a change of strategy and spending cuts brought the project to a premature halt before the cartographic work (as opposed to the interpretative work) could be completed.

In 2008, following advances in geographic information systems (GIS) software and the complete digitization of the UK's geology at 1:625 000 scale (Anonymous 2007*a*,*b*), it was decided to resume he preparation of a national UK engineering geological map. Initially, an attempt was made to incorporate Dearman's original interpretations directly into the digital revisions of the small-scale lithostratigraphical maps. However, this was not feasible because of changes to the map linework, as well as changes in stratigraphical nomenclature and engineering geological standards. Consequently, a complete reinterpretation of the lithostratigraphical maps was undertaken using newly created Engineering Groups (see Table 1) that better reflected modern geological and engineering geological interpretations. An example of the differences between Dearman's original interpretation and the new engineering geological map is shown in Figure 1.

ENGINEERING GEOLOGICAL MAP UNIT		DESCRIPTION
Dearman (1991)	Anon. (1976)	
Engineering Group	Lithological Suite	Many or several Engineering Formations formed under similar geological conditions with certain common lithological characteristics throughout that distinguish the unit from other Engineering Groups. Can be attributed with only general engineering geological properties. Used for small-scale maps.
Engineering Formation	Lithological Complex	A set of genetically related Lithological Types developed under specific geological conditions. Spatial arrangement of Lithological Types is uniform in lithological character or physical state. Not possible to define geotechnical properties for the whole unit (only for the Lithological Types) General engineering behaviour can be indicated. Used for medium- and some small-scale maps.
Lithological Type	Lithological Type	Homogeneous in terms of mineralogy, texture and structure. Defined by petrographic investigation. Used for large-scale maps.
Engineering Type	Engineering Geological Type	Uniform in its physical state. Can be discriminated on the basis of say, weathering state, discontinuity frequency and pattern, strength or consistency. Distinctive geotechnical properties. Used for large-scale maps and engineering geological plans.

Table 1 – Descriptions of engineering geological map units, summarised from Dearman (1991).

The purpose of these small-scale engineering geological maps is to present an overview of the engineering geology of the UK. The data on the maps should not be used as a definitive measure of what is in the ground, but rather as an indication of what may be there. They are, of course, not intended as a replacement for detailed site-specific desk studies or ground investigations, hence the limited amount of geographical references such as roads and towns displayed on the map faces. The maps may prove of particular use to those who are embarking on the study of engineering geology or who are in the early stages of their professional career. They may also serve to help increase the awareness of those in related professions as to the impact of geology on planning and development, and act as a reminder of the importance of engineering geology to reducing the risks associated with human interaction with the built and natural environment.

This paper describes the methodology used to produce the 1:1 000 000 scale engineering geological maps for superficial deposits and bedrock of the UK and discusses how the maps might be used, their limitations and possible future applications.

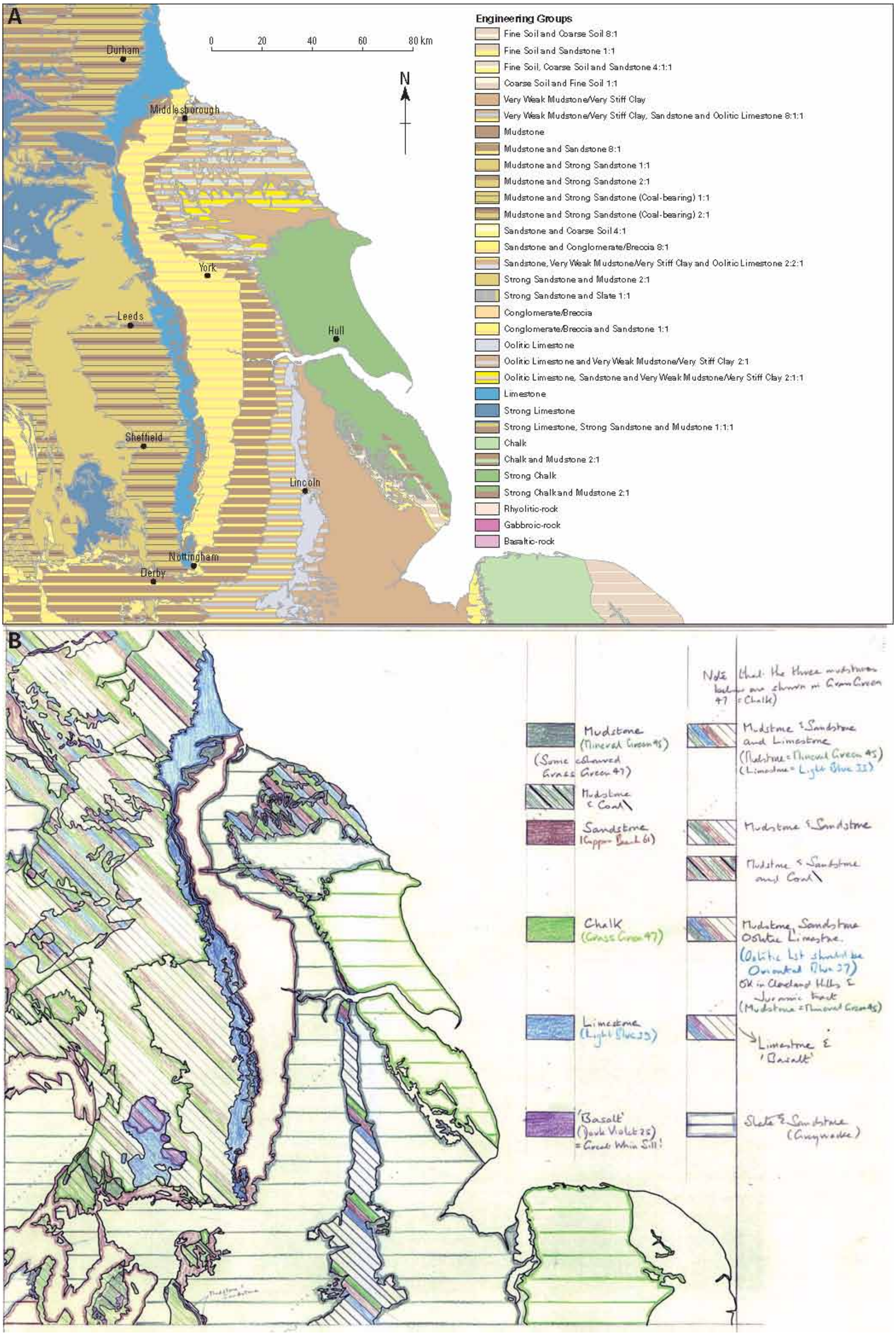


Figure 1 – Comparison of 2011 Engineering Geology (Bedrock) Map with Dearman's 1996-97 hand drawn interpretation.

Methodology used for interpreting the engineering geological maps

There are many ways in which rocks can be classified. Traditionally (and slightly oversimplified), geological maps have adopted a lithostratigraphical approach, based on common rock type, or a chronostratigraphical approach, based on common age. In many instances these two different approaches are used in tandem. Lithostratigraphical nomenclature often comprises type locality or area, lithology and unit term (Hedberg 1976; Whittaker *et al*. 1991); for example, the London Clay Formation. However, lithology can be, and often is, omitted. Furthermore, there are many examples of older rock names, which have not been updated to reflect the formal lithostratigraphical nomenclature formally adopted by the British Geological Survey in the 1990s and summarized by Powell (1998). The use of this system is not ubiquitous across the UK and many ambiguous and even misleading names are still in use. Many units may only reference the type locality, such as the 'West Walton Formation' or the 'Scarborough Formation'. They may include lithology but not location, such as the 'Great Oolite Group' and the 'Basal Quartzite Member'. Indeed, some have information about neither, for example, 'Blue Lias Formation'. Even where the full tripartite lithostratigraphical name is used, such as the Bromsgrove Sandstone Formation, it does not impart any information to inform the user that there are also subsidiary conglomerate beds, whether the material behaves as a soil, weak rock or strong rock, etc. As such, traditional lithostratigraphical maps are of limited use for engineering purposes unless supplemented with additional information on the lithologies present and their likely geotechnical properties (physical, mechanical and chemical) and engineering behaviour.

In the UK, there is extensive lithostratigraphical mapping coverage at scales of 1:10 000, 1:50 000, 1:250 000 and 1:625 000. The principles of translating a traditional lithostratigraphical map into an engineering geological map have been discussed extensively (e.g. Dearman 1991) and many such maps, in various forms, have since been produced in many countries. One of the earliest (albeit brief) discussions of the translation of geological maps for interpreting ground conditions was provided in a US Geological Survey Circular (Anonymous 1949). This illustrated 'how a general geologic map can be used for interpreting ground conditions during the planning stage prior to site selection'. Maps were produced showing construction materials, foundation and excavation conditions, problems of underground water supply and sanitary engineering, surface water problems in relation to flood control, drainage and canal construction, and soils and land utilization problems.

The methodology adopted for the compilation of the British Geological Survey's 1:1 000 000 scale engineering geological maps of the UK is largely based on that developed by Dearman for the unfinished 1996–9797 engineering geology maps. This methodology has been utilized to reattribute the 5th Edition 1:625 000 scale UK bedrock geology maps (Anonymous 2007*a*,*b*) and a provisional (and as yet unpublished) 1:625 000 scale UK superficial geology map.

In the UK, a four-level lithostratigraphic hierarchy (as applied to sedimentary rocks) is used on bedrock geology maps (largest first) (after Dearman 1991):

- group: two or more formations;
- formation: fundamental mapping unit of lithostratigraphy; should be conspicuously different from adjacent formations;
- member: named or unnamed lithological entity within a formation;
- bed: named or unnamed single layer.

On superficial geology maps the units shown can be described as mainly lithogenetic, with some chronostratigraphical information, rather than lithostratigraphic because they are defined by the geological process (glaciation, fluvial action, etc.) that caused them to be deposited, as well as lithology. At small scale, lithology tends not to be included as it is likely to be variable.

Anonymous (1976) and Dearman (1991) recognized four engineering geological map units differentiated on the basis of the scale at which they were applied. These are summarized in Table 1.

As with Dearman's 1996–1997 interpretation and Dearman & Eyles' 1982 map, lithostratigraphic and lithogenetic map units from the basic geological maps were recast as engineering geological map units. Because of the scale of the engineering geological maps, in the case of the engineering geological bedrock map, these engineering geological map units should be termed engineering groups (Table 1).

An extended key has also been produced to accompany the maps. It provides detailed information on the typical behaviour and engineering characteristics for each of the engineering geological map units. In addition, each of the map faces has extensive marginalia in the form of text-boxes, schematic diagrams and very small-scale (*c*. 1:7 500 000 scale) inset maps to impart additional information that could not be readily incorporated into the main maps.

Map attribution

Each of the 243 lithostratigraphical bedrock units (including sedimentary, igneous and metamorphic rocks) and 14 lithogenetic superficial deposits units shown on the 1:625 000 scale bedrock and superficial geology maps respectively, were separately assessed. The first step was to determine the dominant lithology, or lithologies, present within the unit and then to characterize these lithologies in terms of their geotechnical properties and engineering behaviour. Lithology, mineralogy, grain size and texture were determined using the BGS Lexicon of Named Rock Units (Lowe 1993), BGS geological map sheet explanations (mainly at 1:50 000 scale) and geological memoirs and BGS and Geological Society Regional Guides. Geotechnical property and engineering behaviour information were obtained from assessment of the BGS strength dataset (Busby *et al*. 2009), the BGS National Geotechnical Database (Self & Entwisle 2006), BGS engineering geological reports on selected UK groups and formations (Forster *et al*. 1994; Hobbs *et al*. 2002, 2005) and thematic or applied geological mapping reports (reviewed by Culshaw *et al*. 1988; Smith & Ellison 1999).

The lithologies were then categorized using a newly developed engineering lithology classification scheme. The drafting of the classification scheme and the categorizing of lithologies was iterative, the categorization process itself helping to inform and refine the classification scheme. The bedrock lithostratigraphical and superficial deposits lithogenetic units were then reattributed as engineering geological map units (engineering groups). Furthermore, from geological mapping at larger scales (mainly 1:50 000), borehole records held in the National Geological Record Centre and descriptions within BGS local and regional geological memoirs, the lithological variation of each engineering group was ascertained so that relative proportions of each lithology within an engineering group were determined. Each engineering group has between one and four distinct engineering lithologies within it. The varying proportions of these engineering lithologies were shown using different colour stripes. A stripe system was used as it was considered the clearest method of representing multiple engineering lithologies on maps at the scale used (Figures 1 and 2). The engineering lithologies are defined by having similar lithological characteristics (regardless of age) and anticipated geotechnical properties and behaviour. Engineering groups on the engineering geology superficial map are based on single dominant lithogenetic units derived from the superficial deposits geological map but modified in some cases (see below). Figure 3 shows an example of the way in which engineering groups are shown on the engineering geology superficial map. A schematic diagram of the workflow process is shown in Figure 4.

In practice, the re-attribution of geological map polygons (the lithostratigraphical and lithogenetic units) was achieved by adding a new field to the existing geological layer attribute table (within the GIS) and populating this field with the new engineering geological map 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 was 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.

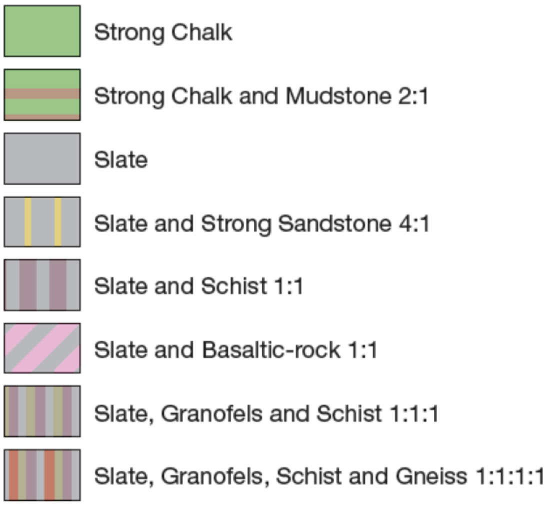


Figure 2 – Example of the stripe system used for the Engineering Geology (Bedrock) Map.

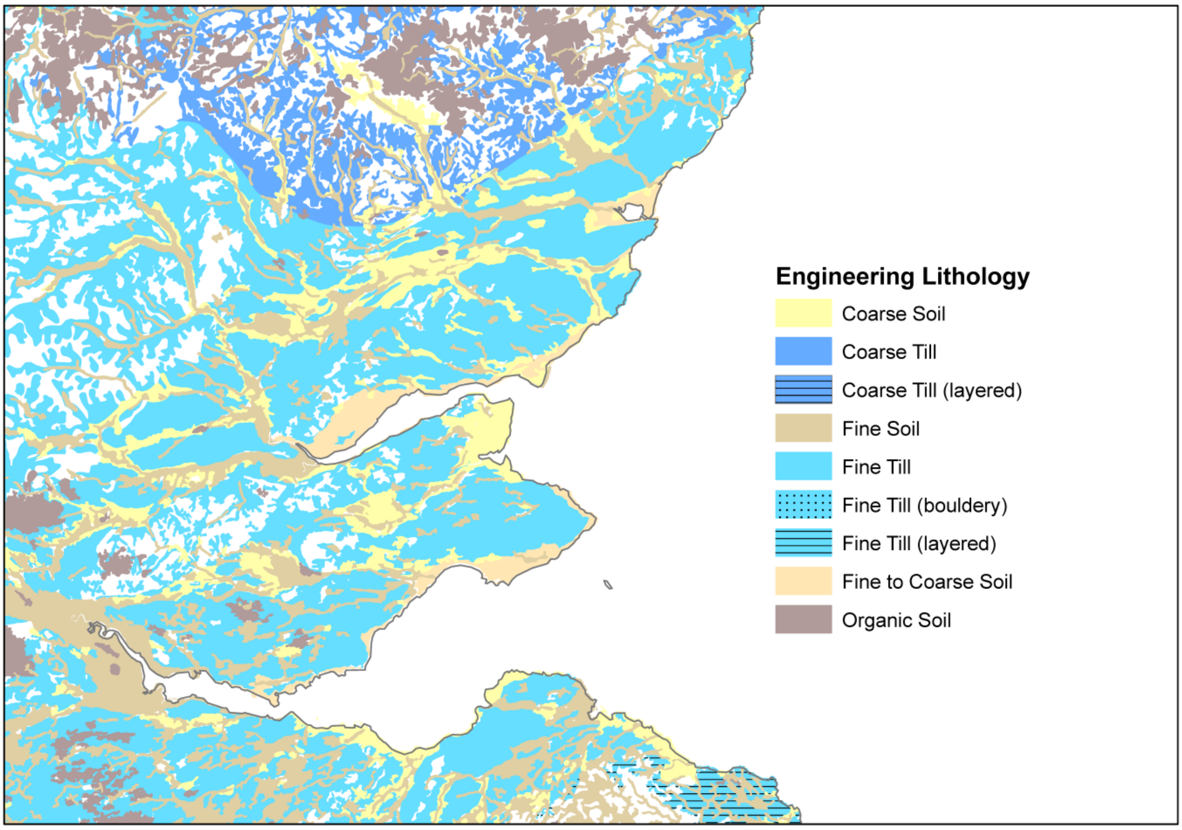
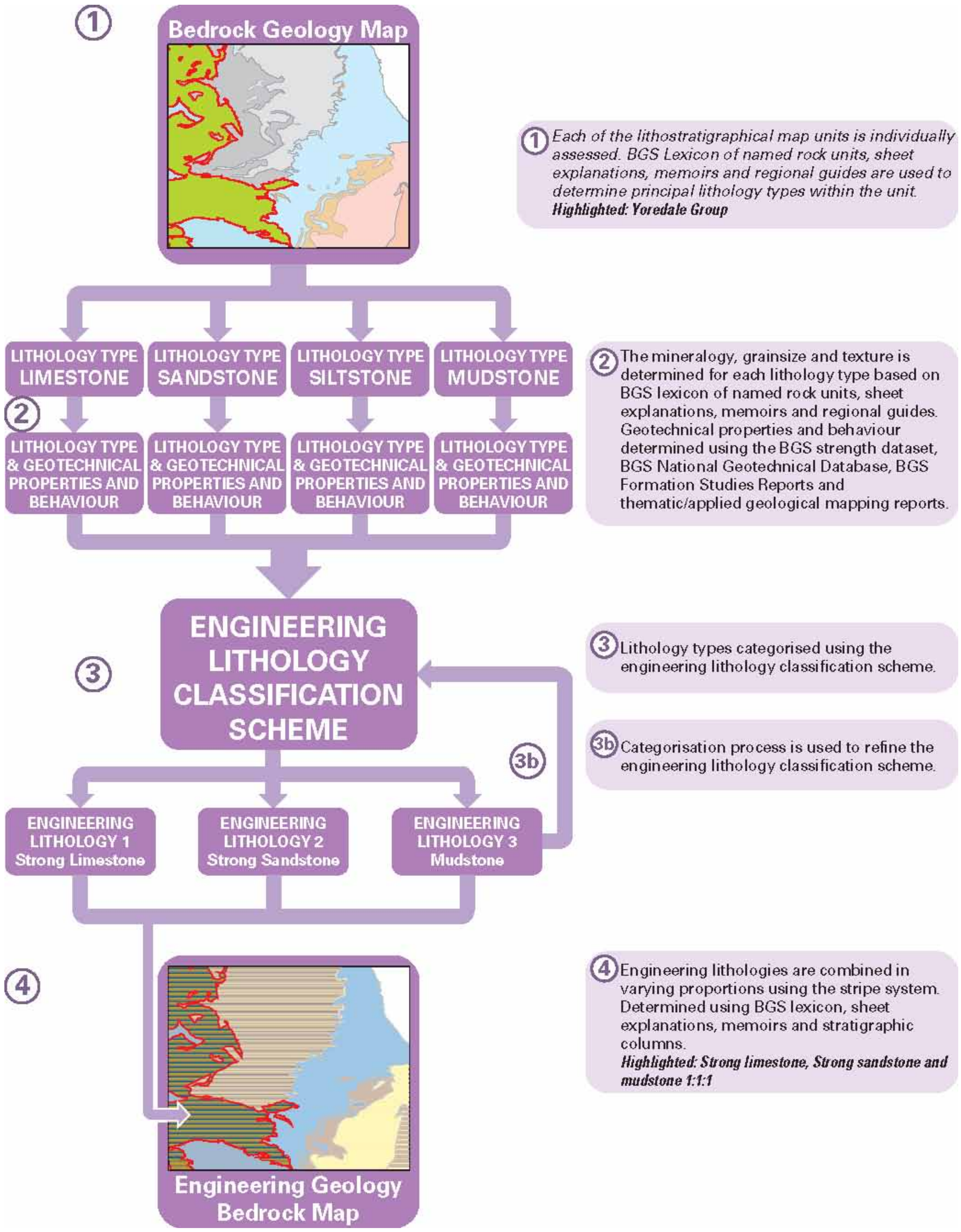


Figure 3 – An extract from the Engineering Geology (Superficial) Map.



① *Each of the lithostratigraphical map units is individually assessed. BGS Lexicon of named rock units, sheet explanations, memoirs and regional guides are used to determine principal lithology types within the unit.*
Highlighted: Yoredale Group

② The mineralogy, grainsize and texture is determined for each lithology type based on BGS lexicon of named rock units, sheet explanations, memoirs and regional guides. Geotechnical properties and behaviour determined using the BGS strength dataset, BGS National Geotechnical Database, BGS Formation Studies Reports and thematic/applied geological mapping reports.

③ Lithology types categorised using the engineering lithology classification scheme.

3b Categorisation process is used to refine the engineering lithology classification scheme.

④ Engineering lithologies are combined in varying proportions using the stripe system. Determined using BGS lexicon, sheet explanations, memoirs and stratigraphic columns.
Highlighted: Strong limestone, Strong sandstone and mudstone 1:1:1

Figure 4 – Process diagram showing the synthesis of the Engineering Geology (Bedrock) Map from the 1625 000 Bedrock Geology Map

Engineering lithology classification

One of the most challenging aspects of the interpretation was the drafting of the engineering lithology categories used to attribute the map. At the outset, it was proposed that these units should, where possible: (1) convey the variety of lithologies present, as well as their geotechnical properties and behaviour; (2) be clearly discernible, visually, from one another; (3) have names that were unambiguous, familiar and, where possible, in keeping with both British Standard BS5930 (Anonymous 1999) and the BGS Rock Classification Scheme (Gillespie & Styles 1999; Hallsworth & Knox 1999; Robertson 1999).

The engineering lithology categories derived for these maps are not intended to be a new, all-encompassing, classification system. Rather, they are intended to accurately and succinctly represent the engineering geological properties of UK rocks and soils at a scale of 1:1 000 000. As such, there are many simplifications and outright omissions that were deemed appropriate for the production of maps at this scale. Furthermore, artificial ground has not been included as it is not mapped at an appropriate scale; however, its classification (Price *et al.*, 2010, 2011) is included in the marginalia of the engineering geology (superficial) map.

Engineering geology (bedrock) map

The first major subdivision in the engineering geological classification is based on genetic origin, with which all geologists and many non-geologists are familiar: sedimentary, metamorphic and igneous. There are distinct differences in engineering behaviour of these three groups. Where multiple engineering lithologies were represented in a unit, the stripe system described above was used with the stripes oriented horizontally if the rocks were of sedimentary origin, obliquely if igneous, and vertically if metamorphic. An example is shown in Figures 1 and 2.

The engineering geological interpretation was based on the unweathered material likely to occur within the top 20 m of the outcrop, or subcrop if below superficial deposits. Although deep weathering profiles do exist in some lithological types (e.g. granite in SW England) the interpretation did not take this into account owing to the scale at which the maps have been produced. However, details of likely weathering profiles are provided in the description of engineering lithologies in the extended key.

For the engineering geology bedrock map, a total of 243 lithostratigraphical map units were converted into 22 engineering lithologies. These were combined in various proportions using the stripe method to produce 67 engineering geological map units.

Sedimentary

Figure 5 shows the engineering lithological divisions recognized for the sedimentary rocks class and the variables used to discriminate between them. The first subdivision within the sedimentary rocks class is made on the basis of mechanical behaviour; that is, whether the material responds to stresses in a way that obeys the laws of solid mechanics (rock) or particulate mechanics (soil). The definition provided by Terzaghi & Peck (1967) defines rocks as aggregates of minerals connected by strong and permanent forces, whereas the mineral grains in soil can be separated by gentle mechanical means such as agitation in water. Terzaghi & Peck went on to acknowledge that their definition of the soil–rock boundary is arbitrary given that the terms ‘strong’ and ‘permanent’ are subject to different interpretation. Clearly, there is some overlap in the transition in behaviour from soil to rock; the implications of this are discussed later in this section.

The second subdivision is based on chemistry to differentiate between rocks that are carbonate-rich and those that are not. Carbonate-rich rocks are prone to dissolution and have different hydrogeological and weathering characteristics. Engineering soils are not subdivided by chemistry as this does not produce the same behavioural variability as that found within rock. Additional chemical differentiation, for example to distinguish evaporite–salt deposits, has not been made as this is considered inappropriate at this scale. Information about soluble rocks is included as an inset map within the engineering geology bedrock map marginalia.

Grain size is the basis for the third subdivision to differentiate between mudstone, sandstone and conglomerate within the noncarbonated rocks, and between chalk, limestone and oolitic limestone within the carbonate-rich rocks. This is important because many aspects of the engineering behaviour, such as permeability, strength and deformability, are influenced by grain size.

Subdivision thus far has been based largely on lithology, as lithological classification is largely determined by chemistry and grain size. The fourth subdivision is based on strength, as this is a key parameter for most aspects of geotechnical engineering. As with the previous classes, subdivision is made only where there is an unambiguous and significant amount of variation in the likely engineering properties and behaviour of the rock. Although separate strength subdivisions are appropriate for chalk, limestone and sandstone, they are not for conglomerate or breccia, or mudstone. Conglomerates or breccias are not present in sufficient quantities, at this scale, to merit subdivision in terms of strength and, in the UK, strong mudstones usually have a slaty cleavage and so are represented in the metamorphic category as slates. However, the class ‘Very stiff fine soil/Very weak mudstone’ is introduced to address the particular engineering considerations that arise from clay-rich sediments that straddle the boundary between very stiff soil and very weak rock. A similar class is not introduced for ‘Sandstone’. Whereas the transition from soil to rock within clay-rich rock is often gradational, the soil–rock transition within sandstone is often more abrupt (partly because of cementation), with sand and sandstone frequently occurring as interbeds, particularly within the Cretaceous. These occurrences can be represented by stripes of coarse soil and sandstone in the same engineering geological mapping unit, a solution not possible for very stiff fine soil or very weak mudstone material. Because of the many geohazards associated with the legacy of coal mining in the UK (Culshaw *et al*. 2000), areas where workable coal seams may occur are indicated by a thin black line as shown in Figure 1.

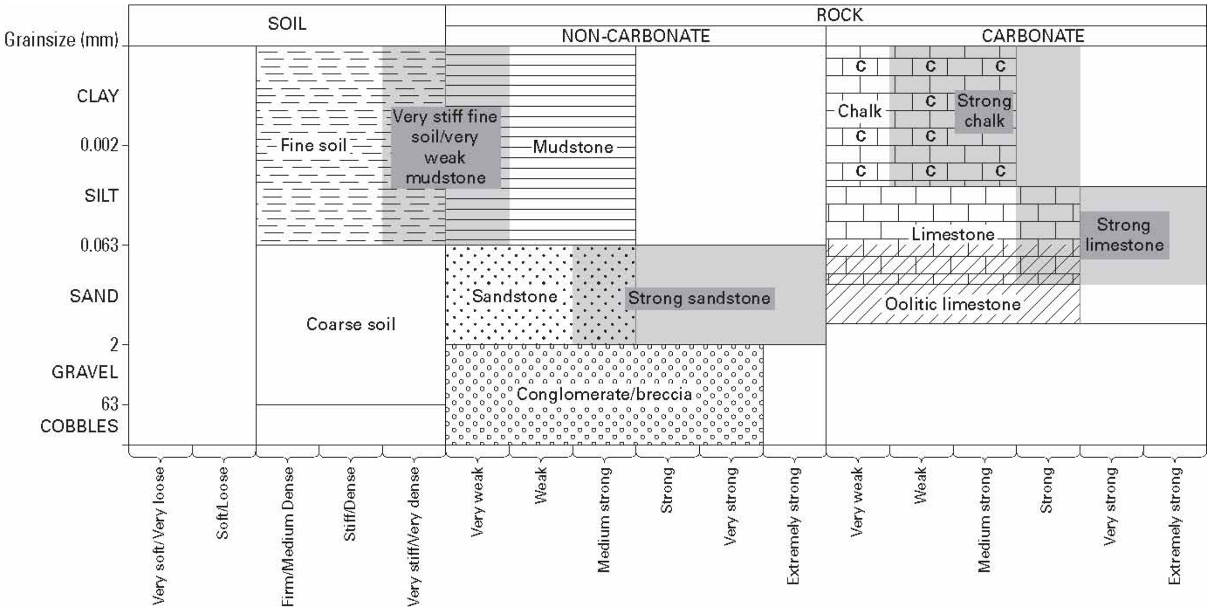


Figure 5 – Engineering Lithology subdivisions for sedimentary rocks.

Metamorphic

Metamorphic rock classification is a tortuous and often controversial subject and, in the authors' experience, does not appear to have been well addressed in engineering geological classifications generally. Several classification systems exist, varyingly based on type of metamorphism, protolith, pressure, temperature, mineral assemblages, texture, chemistry and combinations thereof (Yardley 1989; Smulikowski *et al*. 2007). However, despite the prolific number, or perhaps even because of them, many terms remain ambiguous and contradictory (Fettes & Desmons 2007). As a consequence, there is a great deal of variability and inconsistency in the terms used to describe metamorphic rocks, as they are often subject to the prejudices of those undertaking the work (Gillespie & Styles 1999). This is only compounded by the fact that the boundaries between rock types within these schemes are often gradational, making absolute classification very difficult. Recent work by the International Union of Geological Sciences (IUGS) Sub-commission on the Systematics of Metamorphic Rocks has attempted to resolve these issues (Fettes & Desmons 2007). The BGS rock classification scheme for metamorphic rocks is largely based on the recommendations of the Sub-commission.

The BGS has adopted a very basic lithological classification based principally on protolith and mineralogical composition (Gillespie & Styles 1999). For example, metasedimentary rocks are primarily classified as pelite, semipelite, psammite (for rocks composed largely of quartz, feldspar and mica) and metacarbonate rocks or calcsilicate rocks (for rocks composed largely of calcsilicate and carbonate minerals). The benefit of this classification scheme is that it is simple and unambiguous, allowing for consistency in mapping and within the literature. The major problem for engineering geological purposes is that the mineralogy and protolith of a rock conveys little about the geotechnical properties and engineering behaviour of the rock. One of the dominant factors affecting the engineering characteristics of a metamorphic rock is texture. There is a far greater difference between the physical and mechanical properties and behaviour of, for example, a pelitic slate and pelitic gneiss than there is between a pelitic gneiss and a psammitic gneiss. Figure 6 shows the subdivision of engineering lithologies that fall within the metamorphic category and the variables used to discriminate between them.

The first subdivision within the metamorphic rocks class is based on texture. The BGS root classification names of 'Slate', 'Schist', 'Gneiss' and 'Granofels' based on texture (Gillespie & Styles 1999) were adopted as these were considered to be simple, unambiguous and consistent. The only term not widely used, and not present within the British Standard BS5930 (Anonymous 1999) and so possibly unfamiliar to UK engineering geologists, is 'Granofels'. The use of 'Granofels' is considered justified as it is the only term that unambiguously describes a non-foliated, fine- to coarse-grained metamorphic rock. The term includes quartzites, hornfels and amphibolites. The term 'Granulite' was considered but ultimately rejected as this is associated too often with the granulite facies and, therefore, implies a specific grade of metamorphism.

In addition to the BGS textural root classification names of 'Slate', 'Schist', 'Gneiss' and 'Granofels', two other engineering lithologies, 'Mylonite' and 'Marble', were included. 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 zone complexes. 'Marble' is used for a strong metamorphic rock containing >50% by volume of carbonate and/or calcsilicate minerals.

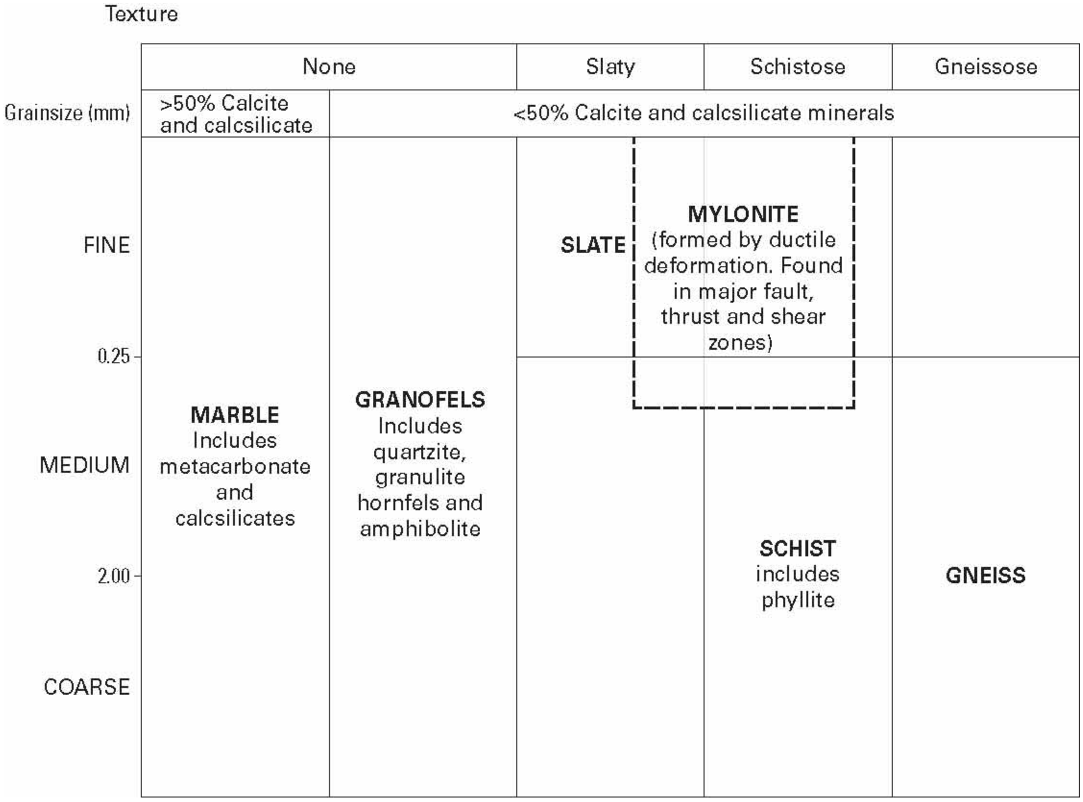


Figure 6 – Engineering Lithology subdivisions for metamorphic rocks.

Igneous

Figure 7 shows the subdivision of engineering lithology for igneous rocks and the variables used to discriminate between them. The subdivision of igneous rock classes has been made on the basis of mineral chemistry and grain size as these are the two factors that most affect the geotechnical properties and engineering behaviour of igneous rocks. At the map scale used, medium-grained igneous rocks are not classified separately from coarse-grained rocks as their engineering behaviour, particularly with respect to strength and jointing, is sufficiently similar to justify a combined class. The terms ‘Basaltic-rocks’ and ‘Granitic-rocks’ have been used instead of the more restrictive terms ‘Basalt’ and ‘Granite’, as the former allow inclusion of similar and related rock types distinguished only by the presence or absence of particular minerals. For example, ‘Basaltic-rocks’ includes not only basalt per se but also other fine-grained mafic rocks such as andesite and phonolite.

A separate class has not been created for volcaniclastic rocks as they commonly occur interbedded within other extrusive crystalline volcanic rocks and mappable outcrops at the 1:625 000 map scale are extremely limited. In the case of ‘Basaltic-rocks’, the occurrence of associated volcaniclastic rocks is considered to be relatively minor and not to have significant impact upon engineering considerations, particularly at the map scale of 1:1 000 000. Tuffs and ignimbrites are important rock types in some areas. However, as their geotechnical properties and engineering behaviour is broadly similar to that of the fine-grained felsic rocks they are associated with, they have been included within the ‘Rhyoliticrocks’ class.

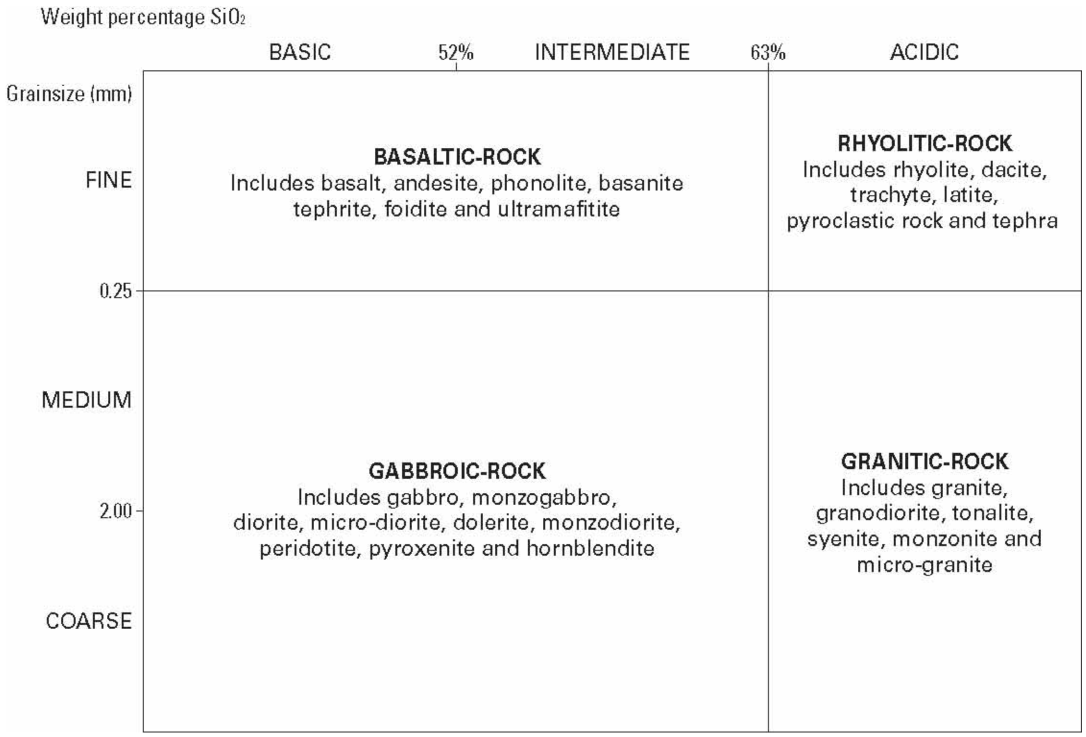


Figure 7 – Engineering Lithology subdivisions for igneous rocks.

Engineering geology (superficial) map

The process of establishing lithological categories for the engineering geology map of superficial deposits was undertaken in a slightly different way from that for the bedrock map. This was because, in part, the BGS 1:625 000 scale superficial deposits geology map does not use lithostratigraphical categories but rather genetic origin to subdivide its mapping units. As there is often a direct correlation between the genetic origin of a geological deposit and its geotechnical properties and engineering behaviour, one option was to use the lithogenetic classification for the engineering geological map. However, as with the engineering geology bedrock map, there existed a number of problems that could create ambiguityes and inconsistencies. Specifically, the ubiquitous use of the term ‘Glacial Till’, with its associated ‘lithological’ description of ‘diamicton’, was considered inadequate when ‘Glacial Till’ varies so much across the UK. Other terms that were similarly variable from an engineering point of view included ‘Head’ deposits, which appears to be a uniquely British geological mapping term, and ‘brickearth’.

Figure 8 shows the engineering lithology subdivisions on the engineering geology superficial map with the variables used to discriminate between them and the original lithogenetic units used. The principal criteria for classification of the engineering lithologies are grain size and organic content. However, a separate set of subdivisions for ‘Glacial Till’ is also included. The inclusion of the term ‘Glacial Till’, despite its genetic origin, is justified by the use of additional qualifiers and because the term has strength connotations.

Although the current 1:650 000 scale superficial deposits geology map presents all glacial till deposits as a single unit, research is under way at the BGS to separate glacial tills into Groups, Sub-Groups, Formations and, in some cases, Members. Groups are divided on age (Anglian or Devensian glaciation), Sub-Groups contain formations and lithogenetic units of similar lithology and geographical extent; formational status is assigned to primary, regionally significant mappable areas based on lithology and physical characteristics; and discontinuous mappable units such as separate till units within a till sequence deposited during the same glaciation may be assigned formation or member status (McMillan *et al*. 2004; Culshaw *et al*. 2010). This work has allowed, for the first time, the glacial till deposits of the UK to be characterized in terms of their general geotechnical properties and engineering behaviour at a national scale. The engineering lithology classes of the glacial tills reflect the primary lithological type (i.e. fine- or coarse-grained), engineering characteristics (i.e. stiff or dense) and secondary characteristics that are of engineering importance. These include layered, coarse-grained beds and laminated clay and silt beds that may, for instance, produce slope stability problems in cuttings.

For the engineering geology superficial map, the 14 lithogenetic map units on which the map was based were converted into nine engineering geological map units (engineering groups). Because of the limited number of superficial deposits and the way in which they are mapped it was not necessary to combine multiple engineering lithologies (e.g. using the 'stripe' method) as was the case with the bedrock map.

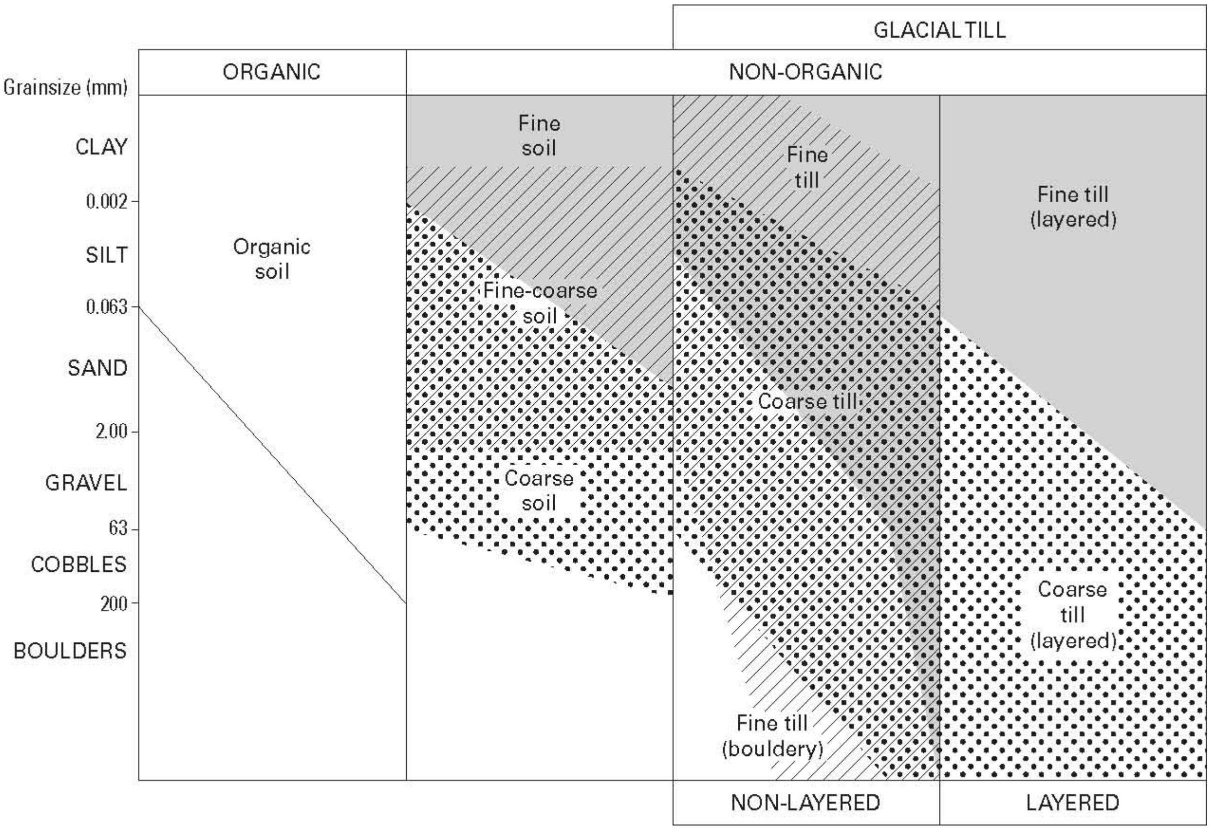


Figure 8 – Engineering Lithology subdivisions for superficial deposits.

Detailed key

A separate sheet containing a detailed key was produced to accompany the maps. It is this key that essentially transforms what might be considered to be basic engineering lithology maps into engineering geological maps. The key provides information for each of the 22 engineering lithologies on the bedrock map and the nine engineering lithologies represented on the superficial map. It includes a description of each engineering lithology (based on generalized BS5930:1999 descriptions; Anonymous 1999) and information on engineering geological considerations, including suitability for foundations, excavatability, use of material as engineered fill and general ground investigation recommendations. The classes shown in the key are based on those used for an engineering geological map compiled by one of the authors (Kevin Northmore) as part of the applied geological mapping of the Bradford Metropolitan District of West Yorkshire in northern England (Waters *et al*. 1996).

DESCRIPTION (After BS5930:1999)	**FOUNDATIONS**	**EXCAVATION (After Pettifer & Fookes 1994)**	**ENGINEERED FILL (After MCHW Vol. 1. Series 600)**	**SITE INVESTIGATION**
Very weak to medium strong usually fissured MUDSTONE. Weathers to a firm to stiff silty clay generally within 2-6 m of ground surface; highly weathered mudstone clasts in a silt/clay matrix may occur to depths of 10-15 m. Generally low permeability, higher permeability in fissured near-surface material; flow dominantly through discontinuities. Includes SILTSTONE and calcareous types.	Generally good foundation conditions, depending on nature and thickness of the weathered zone. In open excavations, foundation levels in moisture susceptible mudstones need protection to prevent rapid deterioration. In some strata potentially high sulphate/sulphide contents and/or shrink-swell movements need to be accounted for in foundation design.	Weathered mudstones may excavatable by hard digging but ripping may be required at depth or for major excavations. Base of excavations may heave on the removal of overburden in wet conditions. Excavated slopes in fresh or slightly weathered material are often stable in short to medium term; weathered and/or fissured mudstones may require immediate support.	Suitable as general granular fill and certain types of selected granular fill if placed under controlled compaction conditions. Should generally be subject to minimum construction traffic when wet. Where present, pyrite-rich material may oxidise and produce acidic, sulphate-rich conditions, which should be accounted for where buried concrete and steel are used.	Important to determine in situ variability in lithology and properties, including depth and nature of the weathered zone. In situ loading tests advisable to assess bearing strength at selected sites. Assessment of shrink-swell potential and sulphate/sulphide contents highly advisable.

Table 2 – An extract from the Extended Key for the Engineering Geology Maps of the United Kingdom showing the engineering lithology ‘Mudstone’.

The variability of each engineering lithology was represented by providing typical ranges for the geotechnical properties and engineering considerations. Where necessary, degrees of uncertainty are indicated in the engineering recommendations by utilizing qualifying terms such as ‘may’, ‘usually’, ‘generally’ and ‘potentially’.

An example of the part of the key for ‘Mudstone’ is shown in Table 2. 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 (Anonymous 2002) and 14689-1 (Anonymous 2003) respectively, and summarized by Anonymous (1999). Several sources were consulted to help compile the key. For example, information regarding permeability was obtained from Bell *et al*. (1986) and from a BGS Open Report on permeability indices (Lewis *et al*. 2006). The criteria for material reuse as fill are based on those of the UK Highways Agency specification (Anonymous 2005*a*). The criteria for excavatability are based on Pettifer & Fookes (1994). Information on foundation conditions and ground investigation was obtained from Dearman’s original work with the BGS between 1996 and 1997 and from the experience of the maps’authors.

Marginalia

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 development, regeneration and conservation but that could not be incorporated into the main maps.

Six inset maps are included on the engineering geology bedrock map. These show structural complexity (after Dearman & Eyles 1982); UK seismic hazard (after Musson & Sargeant 2007); shrink– swell susceptibility of clays and mudstones (based on data in the BGS geohazard GIS (GeoSure; Walsby 2008)); soluble rocks and underground mining (based on data produced by Applied Geology Ltd. (1993), Farrant & Cooper (2008), and Arup (1991) adapted by Jackson (2004), and GeoSure data), sulphate potential (after Forster *et al*. (1995) and Anonymous (2005*b*)) and bedrock permeability (based on permeability indices (Lewis *et al*. 2006)). On the engineering geology superficial map three inset maps are included showing landslide susceptibility (simplified BGS GeoSure datasets), UK Quaternary provinces (Foster *et al*. 1999) and thickness of superficial deposits (based on a BGS dataset summarized by Jackson (2004)). The engineering geology superficial map also includes a number of generic cross-sections showing associations of glacial and alluvial deposits (after Booth *et al*. 2010), block diagrams showing landslide types (after Cruden & Varnes 1996; 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 engineering geology bedrock map has additional text boxes covering faults and shear surfaces, weathering, sulphate hazard and seismicity. The engineering geology superficial map contains text boxes about head, artificial deposits and the extent of UK glaciations. Examples of inset maps and schematic diagrams are shown in Figure 9.

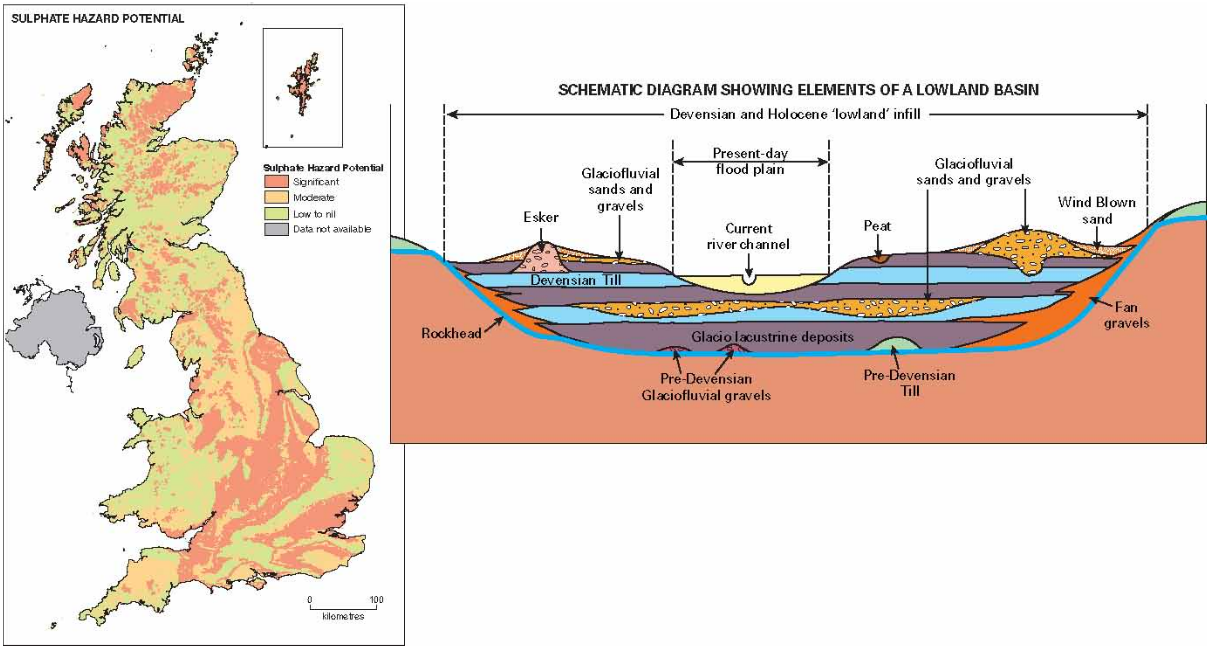


Figure 9 – Extract showing an example of a very small-scale inset map and a schematic diagram used to populate the marginalia of the Engineering Geology Maps.

Discussion

Feedback received from the UK engineering geological community, following invited comments on a draft version of the maps, clearly indicated a desire for engineering geological map information at a larger scale more directly suited to aid site-specific desk-based studies. Consequently, it is intended that aspects of the maps will be extended and incorporated into a value-added dataset based on Digmap50 (the BGS 1:50 000 scale geology digital dataset). This will allow subdivision of the geology at a larger scale. As a digital product, the information could be presented as separate 'layers', allowing the desired properties to be selected and visualized together or as stand-alone options. Even at a scale of 1:50 000 it is emphasized that these non-site-specific maps could only guide, and not act as a substitute for, focused site-specific ground investigations.

Forty years ago, the Geological Society Engineering Group Working Party Report into the preparation of maps and plans in terms of engineering geology (Anonymous 1972) stated that: 'While there is an agreement on the desirability of producing engineering geology maps of the United Kingdom, thus providing more information relevant to the needs of engineers than is available on conventional geology maps, it is felt that it is impracticable to call for national coverage of specially produced engineering geology maps.' However, with the advent of digital geological data and the rapid development of GIS software over the last 20 years, this is now a possibility. Even since the initial BGS collaboration with Professor Dearman in the late 1990s, to produce the present small-scale engineering geology maps described in this paper, the development of 3D digital modelling packages has opened up possibilities for the graphical representation of geological data that was unimagined only a few years ago.

The semi-quantitative and qualitative methods utilized here to express the variability and uncertainty of geotechnical properties and engineering behaviour are appropriate for small-scale maps. However, the user requirements for maps and models at larger scales will necessitate more quantitative methods for expressing variability and uncertainty. A major long-term aim of the BGS is to produce a complete 3D geological model of the UK. With the parallel development and population of digital databases of material property information, the attribution of the 3D spatial models with physical, mechanical and chemical property data is the next step. Research is currently under way to determine the most effective methods for attributing the models with 'point' property data and, importantly, how to best summarize these point data across geological units and to deal with levels of uncertainty in the spatially variable datasets. The integration of additional data, such as those related to groundwater, mineworkings and shallow geohazards, is also possible and has already been undertaken for specific project areas.

Conclusions

The methodology for the production of two new 1:1 000 000 scale engineering geology maps of the UK described here has reinforced the underlying principles of engineering geological mapping illustrated in the publication of the first small-scale engineering geological map of the UK by Dearman & Eyles (1982). Applying these principles has allowed the complex lithostratigraphical divisions of the BGS 1:625 000 scale geological maps to be synthesized into distinct engineering groups of similar lithological and engineering behavioural characteristics. Updates to geological linework and stratigraphical nomenclature since his initial work with the BGS in the late 1990s necessitated modification to Professor Dearman's original interpretation but without compromising the underlying principles used to determine his original mapping divisions.

The digitization of geological data and GIS technology have assisted greatly in production of these engineering geological maps. At 1:1 000 000 scale they are intended to give a broad overview of UK engineering geology and not as a source of site-specific information. It is intended that this technology, along with increased holdings of physical, mechanical and chemical property data in digital databases, will form the basis for the production of larger-scale maps of more direct use to the site-specific needs of the ground engineering industry. The development of 3D geological models and continuing research into the meaningful attribution of these models with physical, mechanical and chemical property data holds even more possibilities of providing ground engineers with engineering geological information tailored to needs at larger regional and even site-specific scales. However, it is vital that with these increasingly sophisticated methods for presenting data, care is taken not to communicate, or appear to communicate, a greater understanding of the subsurface than actually exists. Although it is incumbent upon the creators of engineering geological maps and models to demonstrate both the variability of the substratum and the level of uncertainty associated with our knowledge, it is also the responsibility of the users to appreciate the limitations of the model presented.

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