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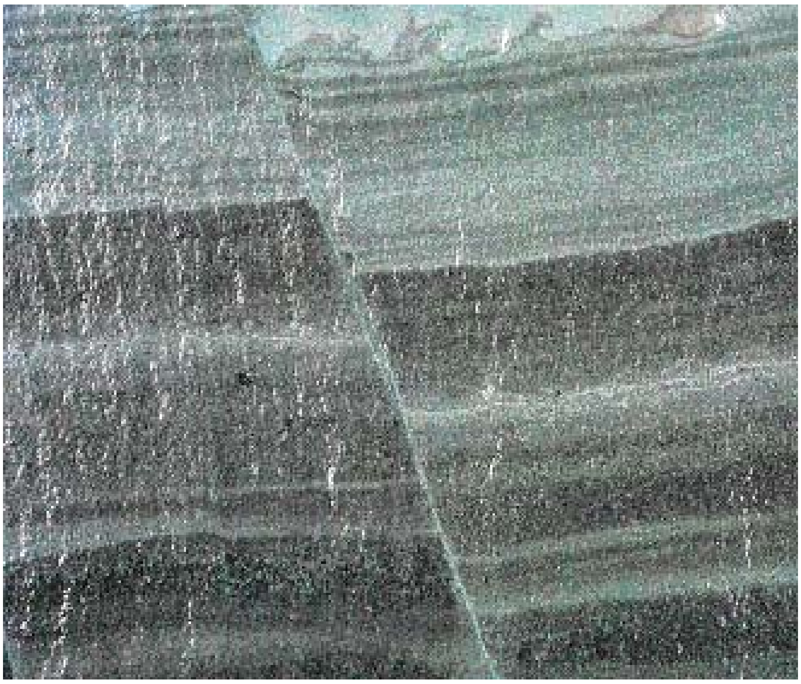
Definition and characteristics of very-fine grained sedimentary rocks: clay, mudstone, shale and slate

Commissioned Report CR/03/281N



BRITISH GEOLOGICAL SURVEY

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Definition and characteristics of very-fine grained sedimentary rocks: clay, mudstone, shale and slate

R J Merriman, D E Highley and D G Cameron

Key words

Clay, mudstones, shales, slate, Aggregates Levy.

Front cover:

Bedding lamination in silt and clay layers offset by faults, displayed on a cleavage plane in Westmoreland Green slate.

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Summary

Clay, shale, mudstone, siltstone and slate are all very fine-grained sedimentary rocks. Their character, including hardness, can vary markedly depending on their geological age and the extent to which they have been buried and altered by tectonic events. In general, therefore, slates and harder mudstone and shales tend to occur in geologically older rocks (pre–Permian > 280 million years). Whilst clays and mudstone are valued for their plasticity, which allows them to be shaped, slates are very hard and durable and economically valued because of their ability to be split along thin parallel cleavage planes. However, the terms slate and shale may be applied to rocks that lack plasticity and a sufficiently well developed slaty cleavage to make of them of commercial interest. These materials may be suitable for use for low-grade aggregate purposes.

1 Introduction

The Aggregates Levy was introduced at the rate of £1.60/tonne on 1st April 2002. For the purposes of the Levy, aggregates are deemed to be sand, gravel and rock with some exceptions. Exemptions that do not fall within the scope of the Levy include shale, slate and clay. Specifically the Finance Act states that:

> 'a quantity of aggregate of any matter is not a quantity of aggregate if it consists wholly or mainly of any one or more of the following, or is part of anything so consisting, namely –
>
> a. Coal, lignite, **slate** or **shale**; ……………..
>
> b. **clay,** soil, or vegetable or other organic matter.'

Problems have arisen with the precise definition of the terms shale, slate and clay. The purpose of this paper is to define these more carefully, in terms of their characteristics and geological origin, in a form that will assist HM Customs & Excise officers' during site visits. However, the original choice of these terms for the purpose of the Act is believed to have been based on their use as economic mineral commodities rather than geological entities. With this in mind, the closely related rocks types siltstone and mudstone have been included in the paper.

2 Identifying very fine-grained rocks

A flow chart with a simplified, step-by-step approach to identifying very fine-grained sedimentary rocks is shown in Figure 1. Clay is readily distinguished from other types of very fine-grained sedimentary rock by its plasticity and ability to be cut and shaped with a knife or trowel (Figure 2). When wet, clay can easily be moulded between the fingers.

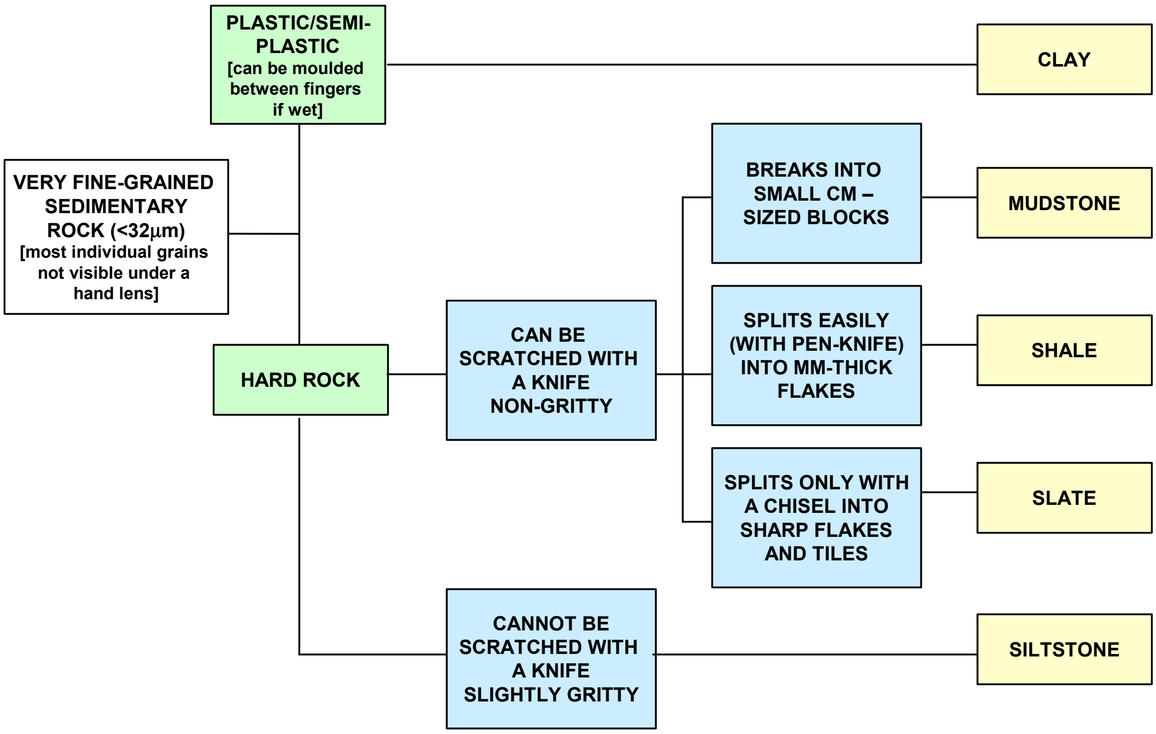

Figure 1 Flowchart to aid identification of fine-grained sedimentary rocks

Figure 2 Some typical clay samples showing grey, grey-green and red colours caused by different oxidation states of iron in the clay. Field of view is 15 cm wide.

Hard, very fine-grained rocks, can be distinguished as mudrock or siltstone in terms of their hardness relative to steel. Because of their high clay mineral content, mudrocks including mudstone, shale and slate, can be scratched with a knife blade or similar steel tool. This will produce a fine, pale grey powder of soft clay mineral gouged from the rock. Typical siltstones (Figure 3), with >50% quartz silt, will not respond to a steel blade in this way. These rocks are harder than steel and will instead remove the metal from the blade and leave a thin, pencil-like metallic line on the rock surface. A slight grittiness is also characteristic of typical siltstones, and can be detected by attempting to crush a tiny chip of siltstone between the teeth. Note that this field test should only be used where there is no risk of ingesting polluted or contaminated material.

Figure 3 Siltstone showing alternating thin bands of silt and silty clay. Field of view is 16 cm wide.

The three types of mudrock can be distinguished by the way they break or split (Figure 1). Mudstones tend to break into polygonal-shaped blocks that are generally 1-5 cm in size (Figure 4). The shape of these blocks is determined by incipient cracks in the mudstone, many of which represent shrinkage cracks generated by diagenetic processes. These cracks may not be apparent in freshly quarried mudstones, but will nevertheless control how the rock breaks when struck with a hammer. When mudstone has been exposed to weathering in a quarry or road cutting, the cracks begin to open. With prolonged weathering the mudstone will degrade into a litter of small blocks whose size and shape is controlled by the system of shrinkage cracks.

Figure 4 Mudstone showing polygonal cracks. Field of view is 15 cm wide.

Shale is characterised by mm-scale laminations parallel with the bedding, called fissility, and will split along these planes (Figure 5). Some shales are soft enough to be split with a pen-knife blade, whereas others require a little leverage with a flat-bladed chisel (bolster), or a tap from the chisel end of a geological hammer. Flat flakes of shale, thin and soft enough to broken by hand are characteristic of split shales. When shale has been exposed to weathering in a quarry or road cutting it parts easily along the fissility, and with prolonged weathering will degrade into a litter of small, paper-thin flakes.

Figure 5 Shale split into thin flakes along the bedding fissility. Field of view is 15 cm wide.

Although slate can be split more perfectly than shale, it generally requires a hammer and a chisel (Figure 6). Unlike shale, the tiles and flakes produced by splitting slate have sharp edges, especially when the rock has been newly quarried. The sound produced when a high-quality roofing slate is struck with a hammer is high-frequency metallic ‘chink’, unlike the dull ‘thud’ produced by mudstone and shale.

Figure 6 Roofing slate. The banding on the cleavage surface is ‘ghost’ sedimentary bedding inherited from the original mud. Field of view is 20 cm wide.

Appendix 1 Properties and definitions

Siltstone, clay, shale and mudstone are very-fine-grained sedimentary rocks. Slate is the low-grade metamorphic equivalent of these rocks. The main constituents are clay minerals and quartz, and they have grain diameters of less than 0.032 mm (<32 μm) (Appendix 4). The small size of these particles is such that individual grains cannot be resolved with the naked eye or with the aid of a hand lens. Shale, mudstone and slate are collectively referred to as 'mudrocks' and are the most abundant sedimentary rock types in the Earth's shallow crust.

Clay, shale, mudstone and slate occur extensively in the United Kingdom (Figure 7). Clay is the least 'mature' of these very-fine grained rocks, and hence occurs most commonly in the younger sedimentary rocks that form outcrops in southern and eastern England. More mature shale and mudstone lithologies are associated with older rocks forming outcrops in central, northern and southwest England (Figure 7). In these regions shale and mudstone are commonly found interbedded with sandstones. Metamorphic slates occur principally in southwest England, Wales and the Lake District, where the main commercial slates are located (Figure 7).

1.1 CLAY

The term **clay** is used for a plastic or semi-plastic sedimentary rock composed of more than 50% clay minerals, and these minerals are typically less than 4 μm (<0.004 mm) in grain size (Appendix 4). Quartz silt, composed of silica (SiO_2), is the main non-clay mineral present. Clay minerals are mostly hydrous alumino-silicates with a platy crystal structure. The chemistry, thickness and stacking arrangement of these platy crystals strongly influences the properties of clay. A high content of very thin platy clay crystals allows extra layers of water to be adsorbed and give the clay plastic properties, i.e. the ability to be shaped and retain a shape. This property may be preserved to varying degrees even when associated silt and sand layers have become lithified to form siltstone and sandstone. When clay is exposed to warm or arid weathering conditions it dries out, hardens, and develops a system of shrinkage cracks (mudcracks). Under normal weathering conditions plasticity is restored to most types of clay by thorough wetting, and the clay swells to fill shrinkage cracks.

Clays show a wide range of colours depending largely on the amount and the nature of iron-rich minerals that they contain. Small amounts of non-oxidized, ferrous iron minerals such as pyrite (FeS_2), tend to give rise to grey clays, whereas oxidized ferric iron minerals such as hematite (Fe_2O_3), give rise to yellow, brown or red clays (Figure 2). Pure white clays are uncommon and usually indicate a high content of one type of clay mineral, such as kaolinite. Black and dark-grey clays indicate a moderate or high organic carbon content. Clay is generally so soft that it can be cut with a knife or sampled with a trowel. This plasticity distinguishes clay from other fine-grained sedimentary rocks.

1.2 MUDSTONE AND SHALE

Mudstone and shale are hard mudrocks composed of variable proportions of quartz silt, with grain sizes less than 32 μm (<0.032 mm), and clay minerals generally less than 4 μm (<0.004 mm) in size. Both types of mudrock may contain silt-rich and clay-rich bands, and show fine bedding on a mm-scale. Some mudstones contain a high proportion of carbonate minerals, such as calcite or siderite, and such minerals may form cm-sized calcareous concretions (or nodules). Some black shales contain a high proportion of organic material and an unusual suite of trace elements. Both types of mudrock have been compacted and hardened by burial in thick sedimentary deposits, and changed mineralogically by diagenetic processes associated with burial.

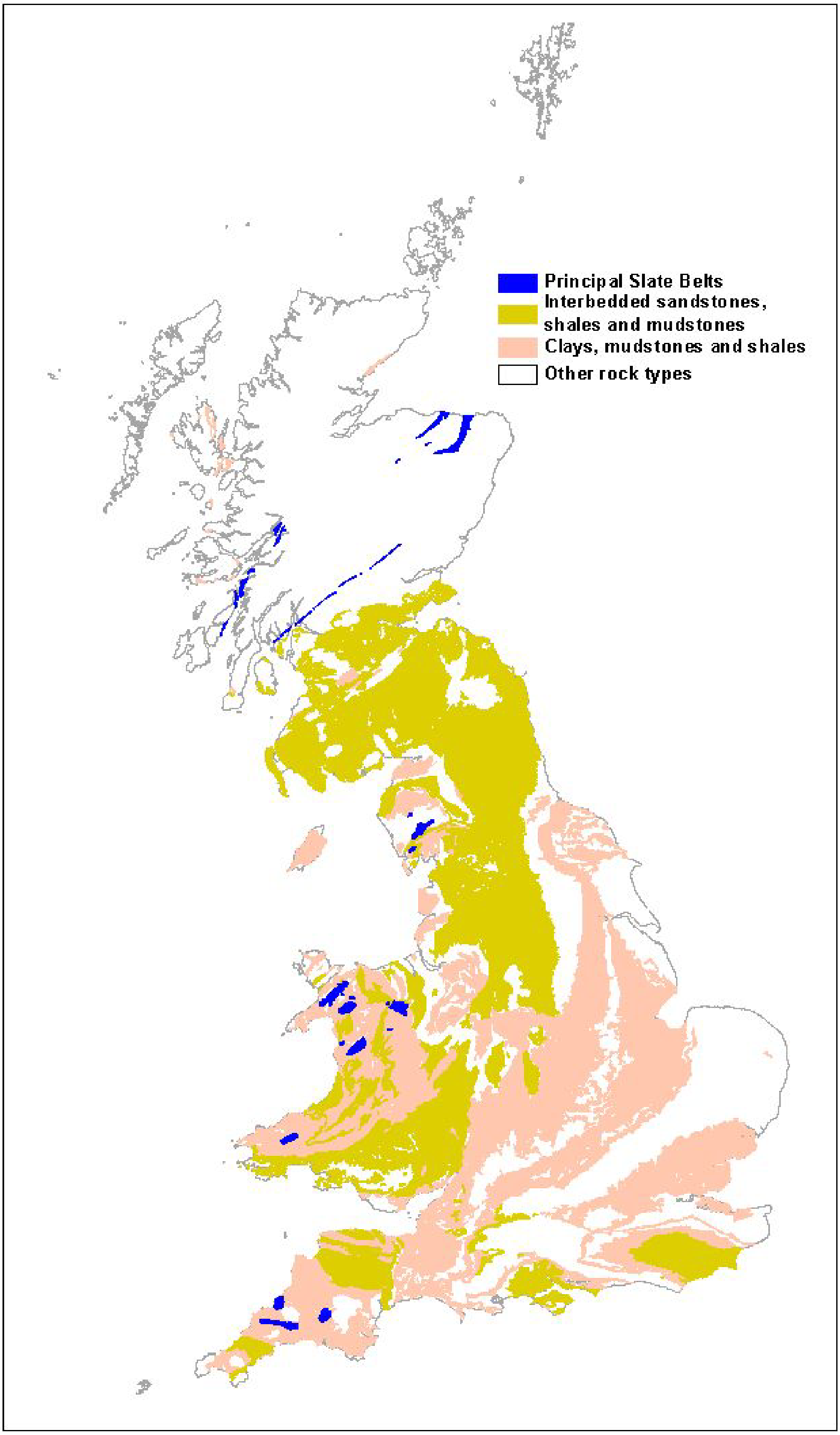

Figure 7 Generalised distribution of clay, mudstone, shale and slate in Great Britain

The two rock types differ in the way they break. Mudstone breaks into small, cm-scale blocks along a series of fractures or cracks that are usually visible when the rock is dry (Figure 4). Shale can be easily split into thin, mm-scale flakes along the sedimentary bedding, otherwise known as a shaley fissility (Figure 5). Some soft shale can be split with a pen-knife or even a thumb nail. In degraded quarry and road cuttings, or weathered outcrops, the different breakdown properties can be observed in the scree or litter produced. Mudstone produces small blocks and granules generally less than 1 cm in size, whereas shale is reduced to paper-thin flakes. Both rocks types also produce much earthy, fine-grained material when they degrade.

In terms of colour, most mudstones and shales show various hues of grey, indicating a high content of clay combined with small amounts of non-oxidized, ferrous iron-rich minerals. Brown or red mudstones and shales may contain oxidized ferric iron minerals such as hematite (Fe_2O_3). Organic-rich shales are dark-grey or black, whereas pale-grey, pale-green or white mudstones may have a high content of one type of clay mineral (e.g. bentonite). Minute brassy crystals are usually pyrite (FeS_2).

Mudstone and shale are brittle rocks that usually require a hammer to remove samples from quarry faces or other rock exposures. While they are too hard to cut with a knife, a pen-knife blade will scratch these rocks and produce a pale grey powder. This is due to a high content of soft clay minerals, which are only weakly cemented in typical shale and mudstone.

Mudstones and shales commonly occur interbedded with sandstones, individual bed thicknesses ranging from less than one metre to a few tens of metres. Consequently, some quarries may extract a combination of mudstone, shale and sandstone.

1.3 SLATE

Slate is the metamorphosed equivalent of mudstone and shale, i.e. the result of heat and pressure applied to these mudrocks. Slate is a hard, splintery mudrock composed of variable proportions of quartz silt and clay minerals with grain sizes less than 32 μm (<0.032 mm). The fundamental feature of slate is the cleavage, which results from well-crystallized platy clay minerals arranged along a single set of micron-spaced parallel planes. Slaty cleavage controls the splitting properties and thickness of slate tiles or flagstones. It is a characteristic of considerable economic importance. Unlike shale, slate can only be split with a hammer and chisel. All previous sedimentary structures, such as bedding or fissility, are replaced during the metamorphic processes that generate slaty cleavage fabric. Although ‘ghost’ sedimentary structures may be preserved (Figure 6) they play no part in the mechanical or engineering properties of slate.

Slate is considerably more resistant to weathering or degradation at outcrop than mudstone and shale. The scree or litter produced typically consists of sharp-edged tiles and flakes no smaller than several centimetres, with little associated fines or earthy material. Slate is a compact, brittle rock that requires a hammer and chisel to remove samples from quarry faces or other rock exposures. Because of the high content of soft clay minerals, a pen-knife blade will scratch slate and produce a pale grey powder.

Grey is the most common colour, but blue, red, purple and green slates also occur widely in the UK. Red and purple slates contain disseminated hematite (Fe_2O_3), whereas grey and blue slates contain variable amounts of pyrite (FeS_2). Green slates may contain a high proportion of volcanic ash. A rusty weathering rind on slate generally indicates variable amounts of disseminated pyrite (FeS_2) that has oxidized by weathering. In some slates, well-crystallized pyrite cubes several mm in size show little sign of weathering.

1.4 SILTSTONE

Siltstone is composed mainly of minerals with grain sizes in the range 4-32 μm (Appendix 4). In a typical siltstone more than 50% of the mineral content is silt-size quartz and the remainder is comprised largely of clay minerals. Many siltstones are finely bedded and consist of alternating layers of quartz silt and clay, with individual laminae no more than a few millimetres thick (Figure 3). This is a primary sedimentary bedding structure produced by regular (or rhythmic) changes in the sediment source. Thin bedding structure is commonly enhanced by sedimentary burial which results in compaction and cementation of the alternating layers, and these may become planes where the rock is easily split into flagstones. Most siltstones are grey in colour, those with a higher clay content showing darker grey colours. Brown or reddish-brown siltstones may contain disseminated hematite (Fe_2O_3).

Siltstone is a compact, hard rock that requires a hammer and chisel to remove samples from quarry faces or other rock exposures. Typical siltstones with a high quartz content are too hard to be scratched with a pen-knife blade, and will instead remove metal from the blade as a thin line on the rock (Figure 1). A slight grittiness distinguishes siltstone from hard mudrocks.

Appendix 2 Uses

2.1 CLAY AND SHALE

Clay, mudstone, shale and, indeed, some siltstones are generically known by the term ‘clay and shale’ when they are extracted for commercial use. Their most important use is in the manufacture of structural clay products, such as bricks, pavers, clay tiles and vitrified clay pipes. Brick manufacture is the largest tonnage use. However, these materials may also be used in cement making, and for lining and sealing landfill sites. Locally they may also be used as a source of low-grade aggregate, for example, for constructional fill. Clay and shale are of different geological ages and compositions. Their mineralogy, chemistry and physical properties, such as particle size, are important in determining their suitability for the manufacture of structural clay products. These factors affect the forming behaviour of the clay (the process prior to firing in which the ware is shaped) and also its behaviour during drying and firing. They will also determine the technical properties of the fired product, such as strength, water absorption (porosity) and frost resistance (its performance in service and durability) and, importantly, its architectural appearance, such a colour and texture.

Clays, mudstones and shales are very widely distributed in the UK. They occur in formations that may be several hundred metres thick, but also may occur interbedded with sandstone and limestone in beds down to less that one metre in thickness. They may also occur as overburden to crushed rock deposits where they can be sold for low-grade fill.

2.2 SLATE

The most familiar use of slate is as thin, but extremely durable, roofing tiles, but there is a continuing demand for architectural slate in other, more decorative, fields. These include dimension stone, wall cladding, paving, sills, fireplaces, tabletops and ornaments for the home and garden. For some of these uses the characteristic property of slaty cleavage is less important and cutting and polishing may be the desired method of shaping and finishing the stone.

Bodies of commercial slate generally have a restricted occurrence within more extensive masses of less perfectly cleaved rock, which accounts for the large tips commonly associated with the industry. The slate belts that are or have been of economic interest in the UK are shown in Figure 8. However, rocks exhibiting a weak slaty cleavage that would be unsuitable for cleaving may be much more extensive but still be classified as ‘slate’.

The term slate has historically been applied to other forms of sedimentary rocks, mainly sandstone and limestone, which can be split to form roofing ‘slates’ or tiles. However, these rely on the cleavage along the original bedding plane rather than metamorphism. They are generally thicker and heavier than true slates.

Appendix 3   Geological origin of mudrocks and siltstone

The main constituents of very fine-grained rocks are clay minerals and quartz silt. Almost all of the common rock-forming minerals can alter to clay minerals during weathering, with the notable exception of quartz. When clay minerals and quartz silt are transported from weathered rock into the sea, i.e. a marine sedimentary basin, they are deposited as soft mud sediments. Compaction and de-watering of soft mud beneath a succession of sedimentary layers results in the early stages of lithification (or hardening) to soft shale and mudstone, which may retain varying degrees of plasticity dependant on the nature and the content of clay minerals. When soft shale and mudstone are buried beneath several kilometers of younger sediment, clay minerals react to increases in temperature and pressure by expelling water and growing larger crystals. These reactions are driven by the very small crystal size, just a few nanometers (nm) thick (1nm = 0.001µm), and crystal-chemical properties of the clay minerals found in compacted mud. Clay mineral reactions together with compactional stresses transform soft or semi-plastic mudrocks into hard mudstone or shale (Figure 8a). Typical mudstones are formed either through the absence of inherited lamination, or a high clay content or because of early carbonate cementation of soft mud. Shale, with a pronounced fissility, is produced by compaction of clay and silt layers in the original soft mud, combined with orientated growth of new clay minerals sub-parallel with the bedding.

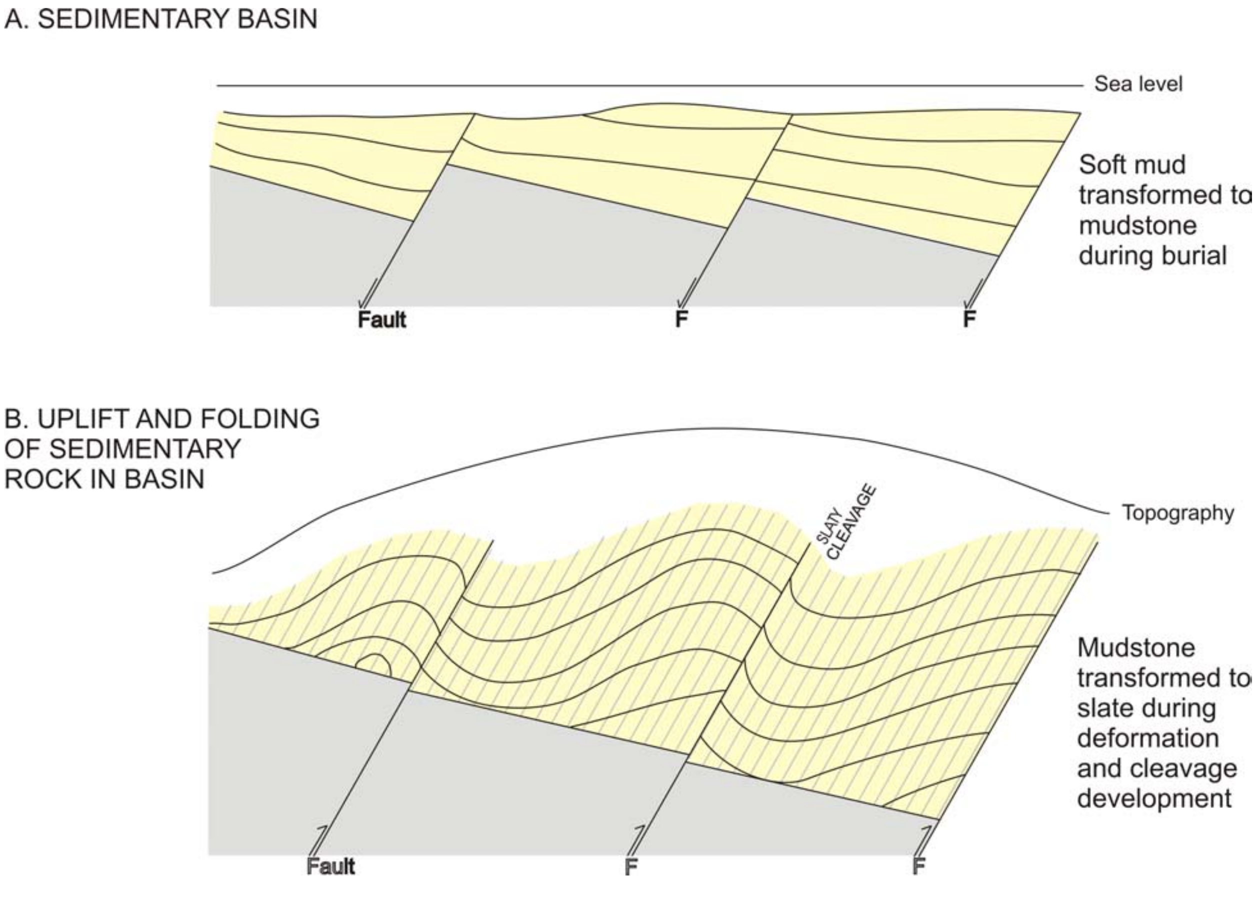

Figure 8 Diagrammatic representation of mud to slate transformation history

The transformation of shale and mudstone to slate occurs when a sedimentary basin is compressed, deformed and metamorphosed during an orogenic (mountain-building) event. Deformation generates folds in sedimentary rocks and during folding the clay minerals in shale and mudstone recrystallise to thicker, platy crystals of white mica and chlorite arranged along a new slaty cleavage fabric (Fig. 8b). The slaty cleavage fabric is formed by a combination of mechanical rotation of pre-existing thin clay crystals, and chemical recrystallization. New white mica and chlorite crystals, forming up to 40% and 15% respectively of a typical slate, grow and thicken along micron-spaced, parallel planes which are generally orientated normal to the direction of greatest stress applied during folding. In a good roofing slate, the cleavage fabric overgrows all previous sedimentary fabrics, such as shaley fissility, allowing the slate to be split to a tile as little as 4 mm thick (Figure 6). Clay crystals of white mica and chlorite in high-grade slates are 2-3 times thicker than those in typical shales and mudstones, and give rise to a hard, durable building stone that can withstand a wide variety of weathering conditions, including industrial pollution. The ideal conditions for the development of slaty cleavage occur when pressures of around 3 kilobars and temperatures of 250-300˚C are generated during sedimentary basin deformation and metamorphism.

Appendix 4 Grain-size and names of some common sedimentary rocks

<table>
<tr><th>Particle Size in mm</th><th>Sedimentary Components</th><th>Unconsolidated Rocks</th><th>Consolidated Rocks</th></tr>
<tr><td></td><td>boulders</td><td rowspan="2">Boulders</td><td rowspan="4">Conglomerate</td></tr>
<tr><td>265</td><td>cobbles</td></tr>
<tr><td>65
16</td><td>pebbles</td><td rowspan="2">Gravel</td></tr>
<tr><td>4</td><td>granules</td></tr>
<tr><td>2</td><td>very-coarse-sand</td><td rowspan="5">Sand</td><td rowspan="5">Sandstone</td></tr>
<tr><td>1</td><td>coarse-sand</td></tr>
<tr><td>0.5</td><td>medium sand</td></tr>
<tr><td>0.25</td><td>fine-sand</td></tr>
<tr><td>0.125</td><td>very-fine-sand</td></tr>
<tr><td>0.032</td><td>silt</td><td>Mud</td><td rowspan="2">Siltstone
Mudstone
Shale
(Slate)</td></tr>
<tr><td>0.004</td><td>clay</td><td>Clay</td></tr>
</table>

Appendix 5 Glossary of terms

Bedding. Generally a planar sedimentary structure produced by layers of sediment deposited on top of each other. Bedding is most obvious where the sediment layers have different grain sizes and/or compositions.

Bentonite. Clay deposit composed largely of volcanic ash that has been altered to one type of clay mineral, most commonly a smectite.

Burial. Progressive increase in overlying thickness of sedimentary deposits that changes the properties of rocks in sedimentary basins.

Calcareous concretion. Hard nodular part of a mudrocks cemented by carbonate minerals.

Carbonate minerals. Minerals in which the carbonate anion (CO_3^{-2}) is combined with Ca, Mg, Fe, or Mn. The most common carbonate mineral is calcite ($CaCO_3$), the main constituent of limestone.

Clay. Plastic or semi-plastic sedimentary rock composed of more than 50% clay minerals with a grain size less than 4 µm (<0.004 mm).

Clay minerals. Hydrous alumino-silicates (with Fe and Mg) composed of very small, platy crystals. The chemistry, thickness and stacking arrangement of clay crystals strongly influences the properties specific clay minerals.

Chlorite. A clay mineral containing a high proportion of iron (Fe) and magnesium (Mg), and most commonly found in mature mudstones, shales and slates.

Crystal-chemical properties. The size, chemistry, surface charge and stacking arrangement of clay crystals.

Diagenetic processes. Changes in the mineralogy and texture of sedimentary rocks resulting from burial in sedimentary basins at temperatures up to 200˚C.

Earth's shallow crust. The part of the crust where sedimentary basins are developed, generally less than 15 km in depth.

Flagstone. A naturally occurring flat rock of sedimentary origin, generally 5-10 cm thick, that can be used for paving, flooring or coping. The thickness of a flagstone is controlled either by its bedding or slaty cleavage.

Gritty. A characteristic of silt or siltstone made up of very-fine grained quartz particles that are too small to detect with the naked eye or a hand lens. The hardness of the quartz particles compared with clay minerals can be detected by crushing a small chip of siltstone between the teeth, producing a gritty sensation.

Hematite. A ferric iron mineral (Fe_2O_3) that produces brown or red colours in clay and mudrocks

Kaolinite. A clay mineral composed of hydrated aluminium silicate, widely used in industrial clay products

Lamination. Thin, mm-scale bedding in mudrocks and siltstones, usually resulting from alternations of silt- and clay-rich bands.

Lithification. The transformation of soft sediment into hard sedimentary rock

Metamorphism. Recrystallization by heat and pressure of primary sedimentary and igneous rocks.

Mudrocks. A collective term for rocks composed clay minerals and silt-sized quartz, including mudstone, shale and slate.

Mudstone. A very-fine grained sedimentary rock composed of clay minerals and silt-sized quartz that lacks a well-developed splitting structure or fissility. Generally breaks into small cm-scale blocks.

Orogenic. Mountain-building process or event caused by the collision of tectonic plates forming the Earth's crust.

Plastic. The property of a material to be shaped or deformed and retain a shape without breaking.

Platy crystal. Crystals that form flat sheets and are characteristic of flaky minerals, such as clays. Individual clay crystals are very thin, commonly between 1 nm and 100 nm (0.001-0.1 μm) thick in typical mudrocks.

Pyrite. A ferrous iron mineral (FeS_2) that produces grey or black colours in clay and mudrocks

Quartz. Silica (SiO_2,) the most common mineral found in sedimentary rocks.

Sedimentary basin. A shallow depression in the Earth's crust, generally much less than 15 km in depth, which has been filled with sedimentary rock

Sedimentary rock. Rock formed by the weathering and erosion of other rocks at the Earth's surface and accumulated as soft sediment in a basin, where it was compacted and lithified.

Shale. A very-fine grained sedimentary rock composed clay minerals and silt-sized quartz that has a well-developed splitting structure or fissility. Generally splits easily into mm-thick flakes.

Shaley fissility. A well-developed plane of splitting in shale, generally parallel with the bedding. Shale can be easily split along the fissility into mm-thick flakes.

Shrinkage cracks. Cracks developed in clay and mudstone caused by dehydration and contraction of clay minerals, either through surface desiccation processes or diagenetic processes.

Silt. Very-fine grained sediment with grain sizes in the range 4-32 μm.

Siltstone. A very-fine grained sedimentary rock composed of more than 50% silt-size quartz with grain sizes in the range 4-32 μm. Some siltstones are finely bedded with alternating layers of quartz silt and clay.

Slate. A low-grade metamorphic mudrock with well-developed slaty cleavage, and composed of variable proportions of quartz silt and clay minerals with grain sizes less than 32 μm (<0.032 mm).

Slaty cleavage. A fundamental feature of slate which results from well-crystallized platy clay minerals arranged along a single set of micron-spaced parallel planes. Slaty cleavage dominates all other fabric elements of the mudrock and can be exploited to cleave the rock into thin (<10 mm) parallel-sided slate tiles, or thicker slate flagstones.

White mica. A collective term for several related clay micas, including illite, muscovite, phengite and paragonite. White micas are the most common clay minerals found in very-fine grained sedimentary rocks.