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Notes

An assessment of lithostratigraphy for anthropogenic deposits

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Abstract: The deliberate anthropogenic movement of reworked natural and novel manufactured materials represents a novel sedimentary environment associated with mining, waste disposal, construction and urbanization. Anthropogenic deposits display distinctive engineering and environmental properties, and can be of archaeological importance. This paper shows that temporal changes in the scale and lithological character of anthropogenic deposits may be indicative of the Anthropocene. However, the stratigraphy of such deposits is not readily described by existing classification schemes, which do not differentiate separate phases or lithologically distinct deposits beyond a local scale. Lithostratigraphy is a scalable, hierarchical classification used to distinguish successive and lithologically distinct natural deposits. Many natural and anthropogenic deposits exhibit common characteristics; they typically conform to the Law (or Principle) of Superposition and exhibit lithological distinction. The lithostratigraphical classification of surficial anthropogenic deposits may be effective, although defined units may be significantly thinner and far less continuous than those defined for natural deposits. Further challenges include the designation of stratotypes, accommodating the highly diachronous nature of anthropogenic deposits and the common presence of disconformities. International lithostratigraphical guidelines would require significant modification before being effective for the classification of anthropogenic deposits. A practical alternative may be to establish an 'anthrostratigraphical' approach, or 'anthrostratigraphy'.

Human activity has modified the geological structure of the Earth and continues to do so at an accelerating rate. Humans are now the major driving force behind geological change, responsible for man-made unconformities and the modification of sedimentary patterns. The anthropogenic modification of sedimentary patterns can be attributed to two overlapping processes (Price *et al.* 2011; Zalasiewicz *et al.* 2011): (1) the creation of novel sedimentary environments and sediments (artificially modified ground), and which is the focus of this paper; (2) modifications to natural sedimentary environments through processes such as damming, coastal reclamation or straightening of rivers (Syvitski & Kettner 2011).

In many novel sedimentary environments, such as urban areas, the landscape and shallow subsurface is dominated by anthropogenic processes, including erosion (i.e. excavation) and anthropogenic sedimentation (i.e. deposits of 'made ground'). This presents a range of potential environmental and engineering challenges including unpredictable ground conditions, geological hazards and contamination (Rosenbaum *et al.* 2003). Anthropogenically modified ground can also offer a record of landscape evolution and the impacts of humans on the natural environment. As such, a range of approaches exist to characterize and classify artificially modified ground to inform activities including land-use planning, development and archaeological study (Edgeworth 2013).

Establishing the geometrical shape and spatial relationships of artificially modified ground requires appropriate systems of characterization and classification. Existing stratigraphical classification schemes used for the geological mapping and modelling of artificially modified ground in Great Britain are largely based on morphogenetic attributes (British Geological Survey 1995; McMillan & Powell 1999; Price *et al.* 2004; Ford *et al.* 2010*a*; Price *et al.* 2011). Morphogenetic classification offers a practical and effective means of differentiating broadly defined classes of artificially modified ground, including worked ground, made ground and infilled ground. In contrast, a lithostratigraphical classification is used for bedrock and, increasingly, for natural superficial deposits based essentially on lithological characteristics and spatial relationships (Salvador 1994). Unlike lithostratigraphy, a morphogenetic approach does not generally allow different phases of artificial ground or lithologically distinct anthropogenic deposits to be differentiated, nor allow the changing magnitude of anthropogenic transformation of the landscape to be determined. A lithostratigraphical approach to classifying anthropogenic deposits could contribute to an improved understanding of the role of humans as major geological and geomorphological

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agents in the Anthropocene (Price *et al.* 2011). The Anthropocene, if defined, will be a chronostratigraphical unit representing a specified time interval. Throughout the geological column, from the late twentieth century onwards, chronostratigraphical and lithostratigraphical schemes have been developed separately. Chronostratigraphical units have typically been recognized as a response to a significant global event, particularly in the context of changing biotic communities. Consequently, the study of the lithostratigraphy of anthropogenic deposits will not be used to define this new age. However, changes in the nature and extent of such deposits, discernible through lithostratigraphy, could provide one line of evidence to consider in deciding if, and how, such a time unit should be defined.

Novel sedimentary environments and anthropogenic deposits share many similarities with ancient depositional systems, including lithological characteristics and successions that conform locally to the Law (or Principle) of Superposition. This suggests that a lithostratigraphical approach may be applicable. However, several characteristics of anthropogenic deposits present a challenge to lithostratigraphical classification, for example:

- Terrestrial anthropogenic deposits vary greatly in both lateral and vertical extent. Although sequences can attain thicknesses of 65 m or more in Great Britain, component units are commonly only a few metres thick.
- By their nature, many anthropogenic units are strictly allostratigraphical; that is, defined and identified on the basis of bounding discontinuities. However, allostratigraphy has not been popularly applied in Great Britain (Rawson *et al.* 2002). The bounding discontinuities can be defined as unconformities (e.g. artificial deposits resting directly upon bedrock), disconformities (e.g. where there is a time gap between parallel layers of artificial deposits associated with either non-deposition or reworking of the deposits) or the present-day land surface.
- Many anthropogenic units, being surficial deposits, have no overlying strata. However, the associated landform may show characteristic features that can aid the definition of a unit.
- Anthropogenic deposits are commonly lithologically heterogeneous, with bulk compositions characterized by considerable quantities of novel, or manufactured, materials.

Although some of these challenges have been previously recognized in the case of natural superficial deposits, they are more marked in the case of anthropogenic deposits (McMillan 2005; McMillan *et al.* 2011).

The aim of this paper is to determine whether anthropogenic deposits can be classified using the same lithostratigraphical procedures employed for natural deposits. The purpose is not to define a lithostratigraphical classification for anthropogenic deposits, but to consider whether such an approach could be used. It discusses where, or in what circumstances, it would work and where it would fail. It also looks at how elements of a pure lithostratigraphical approach can be adapted or incorporated with other classification schemes to offer the functionality necessary to characterize, quantify and investigate the recent geological record, and contribute to the study of the Anthropocene.

This paper is largely based on the study of anthropogenic deposits in Great Britain, including their lithostratigraphical classification to support systematic survey and three-dimensional (3D) geological modelling. However, the value of lithostratigraphical classification in recording and interpreting anthropogenic successions in sections and boreholes and other 'non-geographical' contexts is also considered. Examples from diverse geographical settings highlight the global relevance of establishing effective systems for their classification.

Novel sedimentary environments, artificially modified ground and anthropogenic deposits

It has been recognized that anthropogenic processes that result in the creation of sediments, erosive features and associated landforms can be broadly classified in two main types (Szabó 2010; Price *et al.* 2011; Zalasiewicz *et al.* 2011). The first type comprises those anthropogenic activities that are deliberate, direct and intentional in their modification of the natural landscape. These activities include the excavation, transport and deposition of natural geological materials related to urban development, mineral exploitation, waste dumping and land reclamation to mention but a few. They are termed 'novel sedimentary environments' by Zalasiewicz *et al.* (2011), and are largely unclassified and poorly recorded or mapped. The second relates to the modification of natural sedimentary environments as an indirect consequence of anthropogenic processes such as agriculture, deforestation, damming and the straightening of rivers (Syvitski & Kettner 2011); these factors are not considered here.

Anthropogenic deposits created in novel sedimentary environments may be coeval with natural deposits and those resulting from modified sedimentary environments. The result is a potentially complex record of interaction and feedback between deliberate anthropogenic processes, natural 'background' sedimentation and processes

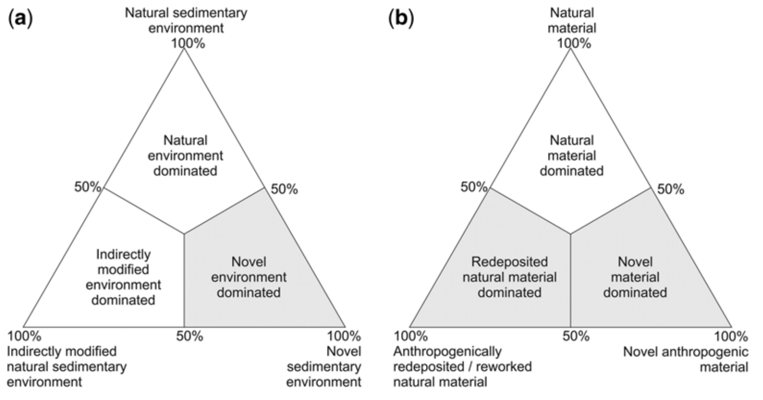

Fig. 1. (**a**) shows the relationship between the natural sedimentary environment, the natural sedimentary environment indirectly modified by human activities and the novel sedimentary environment. Anthropogenic deposits, the focus of this paper, are defined as those dominated by sediment deposited in the novel sedimentary environment (shaded area). (**b**) shows the relationship between novel and natural material in defining the bulk composition of anthropogenic sediments deposited in the novel sedimentary environment. In this diagram, the 'natural material' component reflects input from both natural sedimentary environments and those natural sedimentary environments indirectly modified by human processes. Anthropogenic deposits are defined as those dominated by novel material or redeposited natural material (shaded area).

such as soil formation (Bridgland *et al.* 2006). For the purpose of this paper and the lithostratigraphical classification of anthropogenic deposits, only those deposits that form in dominantly novel sedimentary environments are considered (Fig. 1a).

Novel sedimentary environments are characterized by the anthropogenic alteration of the natural land surface or subsurface through the deliberate creation of sediments (anthropogenic deposits) or voids (excavations) that are together referred to as artificially modified ground (artificial ground). Anthropogenic deposits are taken to include those natural rocks and superficial deposits intentionally moved and redeposited by humans, as well as deposits of novel anthropogenic materials created through manufacture or processing (Fig. 1b) (Norbury 2010). We include in artificial ground natural geological materials that have been displaced, such as spoil from mineral extraction or material moved through landscaping, an interpretation not recognized by Satkūnas *et al.* (2011).

Soils that are created by predominantly deliberate human action, including the addition of novel anthropogenic materials, are included as artificial ground, whereas those that develop through processes such as long-term agricultural cultivation are excluded. Natural materials transformed *in situ* by indirect processes as an unintentional consequence of anthropogenic activity – for example, compaction of soils through construction activity or through contamination by leachates – are not considered here as artificial ground.

Novel sedimentary environments and anthropogenic deposits share many similarities with their natural equivalents. Authors such as Sherlock (1922) propose that 'rocks made by Man' can be classified in a similar way to the classification of natural of rocks to include, igneous, metamorphic and sedimentary types. Examples of igneous anthropogenic rocks include glass, foundry slag and metals. Examples of anthropogenic metamorphic rocks include bricks and ceramics. Examples of anthropogenic sedimentary rocks include concrete. Underwood (2001) refers to those rocks made, modified or moved by humans as 'anthropic rocks' and proposes that they are considered in the rock cycle. Cathcart (2011) recognizes the global significance of anthropogenic erosion and deposition, and proposes that both processes are included in the rock cycle (Fig. 2).

Artificially modified ground within the global rock cycle is significant. It is estimated that the deliberate, annual global flow of anthropogenic sediments is 57 000 Mt (million tonnes), exceeding that of transport of natural sediments to the world's oceans by almost a factor of 3 (Douglas & Lawson 2001). In Great Britain alone it is estimated that over 66 530 Mt of sediment has been moved through the extraction and processing of major mineral resources in around 200 years (Price *et al.* 2011). Locally, Syvitski & Kettner (2011) estimated that approximately 400 Mt of crushed rock and engineering soils were used in one single land reclamation project to construct the Palm Jebal Ali near Dubai in the United Arab Emirates.

It is estimated by Price *et al.* (2011) that around 1.4% of mainland Great Britain is currently covered by significant areas of artificial ground (Fig. 3). By

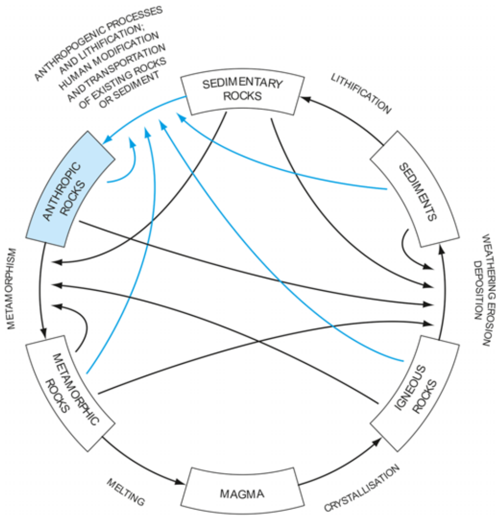

Fig. 2. The Earth's rock cycle including 'anthropic rocks' as suggested by Underwood (2001) and illustrated by Cathcart (2011). Boxes represent materials and arrows represent processes, with anthropogenic processes and deposits shown in blue. Modified after Cathcart (2011).

comparison, mapped alluvium covers only around twice this area when similar map coverage is considered. The extent of artificial ground is typically greatest in urban conurbations where the landscape has been affected by frequent phases of human activity ranging from locally comprehensive cover to an average of 8.2% for the London area (Price *et al.* 2010). About 7% of Great Britain's land cover is designated as urban (UK National Ecosystem Assessment 2011). These areas represent sediment sinks in the novel sedimentary environment, in which humans generate accommodation space for sedimentation by artificially increasing land levels, locally elevating the base level for anthropogenic sediment accumulation and creating environments that potentially favour the preservation of earlier urban strata (Holden *et al.* 2006; Rivas *et al.* 2006; Makedon *et al.* 2009). Rural areas typically show less than 1% artificial ground coverage and represent sediment source areas in the novel sedimentary environment, commonly producing much of the material destined for accumulation in urban and industrial conurbations. These figures, based on British Geological Survey (BGS) data that span several decades, are inevitably underestimates. Prior to the 1990s, artificial ground was not consistently depicted. Since then, the recording and representation of artificial ground on geological maps has generally improved. The current definition of artificial ground as used by the BGS generally refers to landforms and sediments deposited or excavated on or within the shallow ground surface. However, artificial ground is also created at deeper levels in the subsurface. Subsurface artificial ground can be created by processes including underground excavations for mineral extraction, installation of engineered infrastructure and deep burial of wastes. Human intervention and disturbance in the subsurface could be considered a form of 'anthroturbation', similar in nature to other forms of bioturbation.

Although landscaping and earthworks for the construction of buildings are included in this definition of artificially modified ground, as are deposits created from the rubble of former buildings, 'extant' buildings are generally excluded. Arguably, this is an arbitrary distinction as buildings, their foundations and associated earthworks are in physical continuity. This definition recognizes that buildings represent ephemeral sinks and sources of material in the rock cycle, but assumes that their long-term preservation potential is limited. However, in exceptional circumstances, buildings may be preserved relatively intact and form deposits in their own right. Where buildings become preserved in the geological record and structures that are indicative of their function are retained, they may be considered as trace fossils.

The classification of artificial ground including anthropogenic deposits

The importance of understanding the signature of novel sedimentary environments, including the spatial distribution and character of anthropogenic deposits, is recognized by a range of disciplines. For land-use planning, artificial ground represents a potential geological and environmental hazard (Rosenbaum *et al.* 2003). Increasingly, anthropogenic deposits are considered as potential material resources. Reuse and recycling options may include the use of anthropogenic deposits as engineered fill, industrial minerals and feedstock for primary mineral or metal recovery (Waters *et al.* 1996; Lottermoser 2011; Wang & Liu 2012). The value of determining the distribution of historical artificial ground is recognized by archaeological science in the study and management of heritage sites and deposits (Carver 1987; Historic Scotland 2011; English Heritage 2012). The classification and study of artificial ground offers an insight into the distribution and scale of human modification of the landscape and the wider environment.

As a result of this diversity of disciplines and interests, a range of approaches have been used or proposed for the classification of artificial ground. Existing approaches used in geosciences are generally concerned with mapping and modelling the

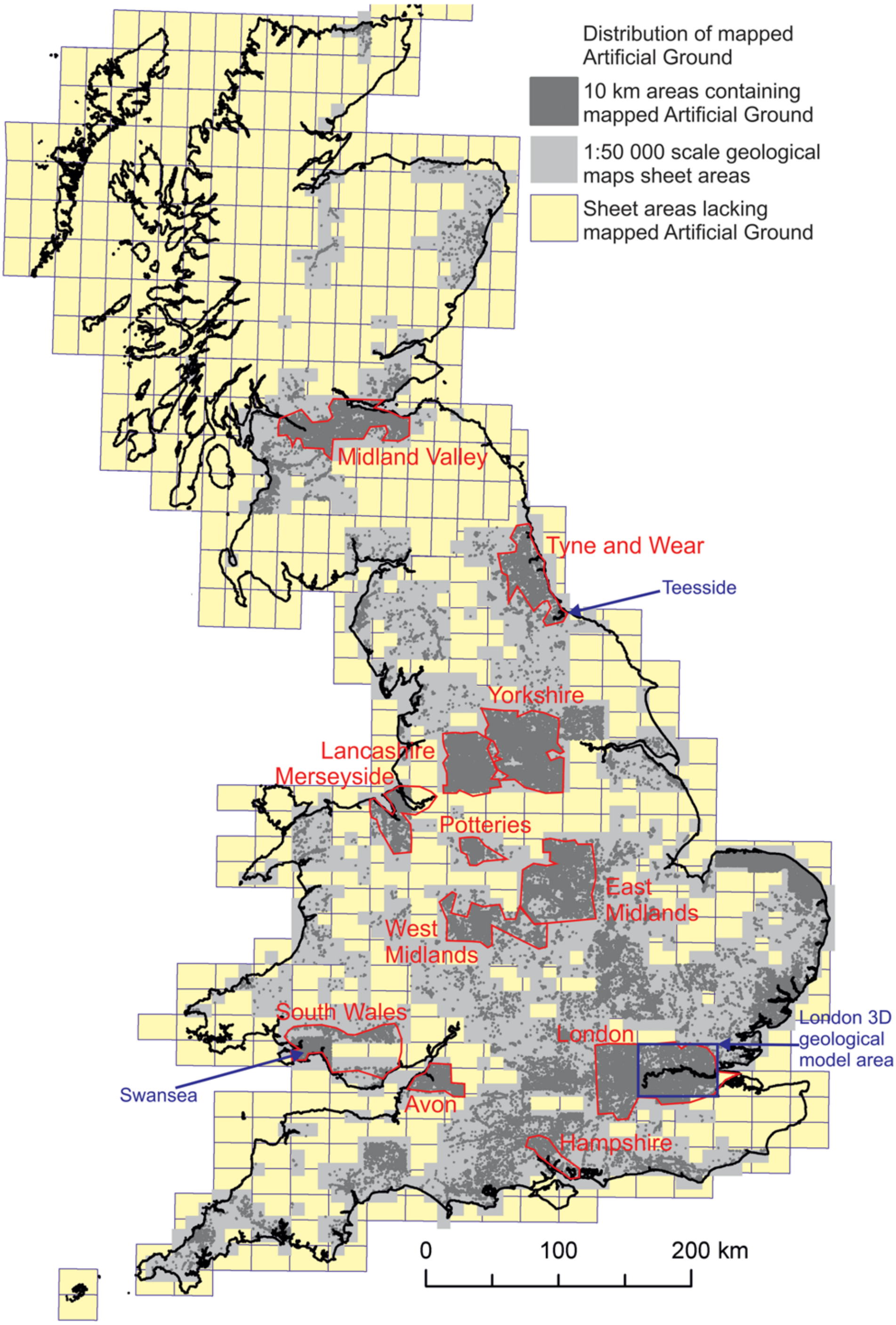

Fig. 3. Maps showing the extent of mapped artificial ground in Great Britain, based on BGS published 1:50 000 scale maps, modified after Price *et al.* (2011). Individual areas of artificial ground have been exaggerated for clarity. Red outlines denote potential domain areas within which artificial deposits may be attributed Group status in any lithostratigraphical classification of anthropogenic deposits. Localities indicated in blue are referred to in the text. DiGMapGB BGS ©NERC. Topographical data ©Crown Copyright Ordnance Survey. All rights reserved.

spatial distribution of artificial ground at a local scale, ranging from 1:10 000 to 1:50 000. Current schemes in use by geosciences are either morphostratigraphical (i.e. morphogenetic) or essentially chronostratigraphical, and no lithostratigraphical classification exists. Topographical surveys depict elements of artificial ground, including road embankments and waste tips, at a range of scales. The requirements of other disciplines vary, with archaeological studies typically operating at a detailed site scale, demanding higher spatial (vertical and lateral) resolution. However, there is considerable overlap between some areas of these disciplines and the geological recording and mapping of artificial ground. The main similarities and differences in the attributes they refer to are discussed below.

Artificial ground classification schemes in use by geoscience

The present British Geological Survey morphostratigraphical approach to artificial ground. Artificial ground has been shown on geological maps published by the BGS for Great Britain since the 1960s (British Geological Survey 1978). However, it was not until the 1990s that mapping of anthropogenic deposits became routine, with the application of a fivefold subdivision into made ground, worked ground, infilled ground, disturbed ground and landscaped ground (McMillan & Powell 1993, 1999; British Geological Survey 1995). This simple classification scheme is based on a morphostratigraphical approach with an emphasis on the landform (morphology) and, to a lesser extent, the anthropogenic process that created it (genesis). Landforms are identified through a combination of field observation and indirect evidence derived from the appraisal of spatial data sources, including aerial photographs, topographical maps including historical maps, contour information and digital elevation models. The combined use of recent spatial data and generations of legacy data allows historical land-use change to be considered and the most appropriate class of artificial ground to be chosen. However, the scheme does not distinguish between different types of artificial ground within each class, and does not allow, for example, the separation of potentially contaminated landfill sites and well-engineered motorway embankments, both of which would be classified as made ground. Similarly, the scheme does not account for different phases of anthropogenic activity that may be represented at any one location.

British Geological Survey enhanced classification scheme. The introduction of digital geological maps and 3D geological models in the 1990s and 2000s offered an opportunity to represent complex spatial relationships involving multiple phases of artificial ground. Consequently, an enhanced classification scheme for artificial ground in two and three dimensions has been devised by BGS (Price *et al.* 2004, 2011; Ford *et al.* 2010*a*). This scheme is structured as a three-tier hierarchy, using ‘class’, ‘type’ and ‘unit’ to describe in progressively more detail the origin and landform of the deposit or excavation (Fig. 4). These subdivisions are presented in a hierarchical relationship, and have been successfully used in urban 2D mapping, 3D modelling and database construction (Waters *et al.* 2005; Ford *et al.* 2008; Price *et al.* 2010; de Beer *et al.* 2012). The scheme is designed to interface with complementary schemes, including the National Land Use Database, which contains information on previously developed land in England (Harrison 2006).

The enhanced classification scheme is morphogenetic, requiring the identification of a diagnostic landform and does not directly incorporate lithological information. Although this scheme is capable of distinguishing different types of artificial ground that would be indivisible using the original BGS classification, it does not allow different phases of artificial ground or lithologically distinct anthropogenic deposits to be differentiated.

Chronostratigraphical classification. A classification of anthropogenic strata that provides the discrimination of materials and boundaries primarily in terms of time has been proposed by Nirei *et al.* (2012). They recognize the following unit types: (a) chronological or ‘chrono-layers’ of materials laid down in a single event; (b) ‘material layers’ consisting of materials laid down in one or more depositional events; (c) ‘bundles’ consisting of a number of adjacent chrono-layers; and (d) ‘associations’ comprising the whole assemblage of units at a site. The scheme, designed to be used to describe anthropogenic successions at specific localities with detailed site investigation data, provides a hierarchical approach comparable to that used in natural successions. However, this proposed scheme combines the concepts of lithology (the material layer) and time-parallel or geochronological layers (the chrono-layers). The chrono-layer most closely relates to the chronosome proposed by Schultz (1982) for rocks of diverse facies representing an interval of deposition identified on the basis of bounding stratigraphical markers. In the case of allostratigraphical units, that bounding marker is a discontinuity (North American Commission on Stratigraphic Nomenclature 2005). In the context of anthropogenic deposits, it is unlikely such boundary markers could be recognizable between disparate sites. Consequently, this scheme does not lend

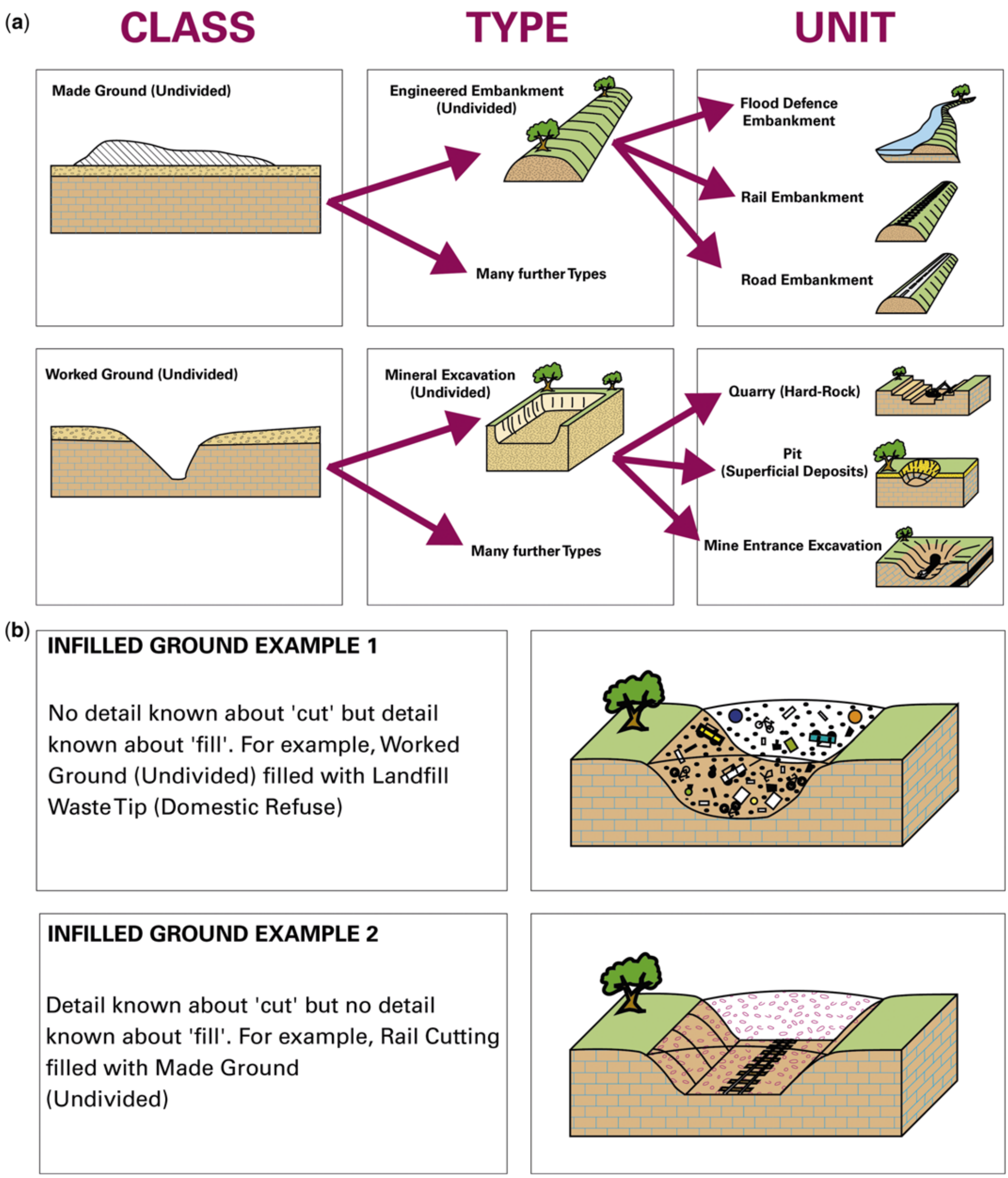

Fig. 4. Schematic diagram showing: (**a**) the structure of the enhanced classification scheme for artificial ground; and (**b**) examples of infilled ground classification derived from the scheme (Ford *et al.* 2010*a*).

itself to mapping and formal stratigraphy, nor the widespread classification of artificial ground.

Artificial ground classification schemes in use by other disciplines

Archaeological recording. Archaeological and geological observation, recording and classification of anthropogenic deposits share many similarities. Archaeologists often refer to the stratigraphical relationship of cultural deposits and structures on the basis of lithological variation, interpreted stratigraphical position and mode of formation. Archaeological description and assessment also considers cross-cutting structures such as foundations, ditches, cellars and basements (Edgeworth

2013). The recognition of assemblages of artefacts, their abundance, and first and last appearance within a sequence of archaeological deposits often provides the basis for the creation of stratification and seriation charts (Carver 1987). Chronology (chronostratigraphy), based on relative or absolute dating, provides the overarching method of correlation. The age of the materials and detail of the artefact content may be referred to as a precise age, an age range, a historical interval (i.e. late Victorian) or a prehistorical interval (i.e. Bronze Age). However, without considerable absolute or relative age information, the application of archaeological classification to the widespread classification of anthropogenic deposits may be problematic.

Classification of urban and industrial soils. The World Reference Base for Soils recognizes two major reference soils groups (RSGs) of anthropogenic soils: Anthrosols and Technosols (IUSS Working Group WRB 2006; Rossiter 2007). Of these, Technosols share some characteristics that are similar to anthropogenic deposits. They comprise at least 20% artefacts in the upper 100 cm of the ground surface (or down to continuous rock or a cemented or indurated layer, whichever is the shallower) or they are sealed by 'technic hard rock' (e.g. pavements and roads). Artefacts comprise novel processed or manufactured anthropogenic materials, and human-transported materials may include redeposited or reworked natural materials extracted from the earth by humans. Where Technosols are dominantly composed of artefacts, they may be considered as anthropogenic deposits in the context of this paper. At a Great Britain national level, hierarchical classification schemes for anthropogenic urban soils have been proposed. Hollis (1992) introduced two classes of urban soils called 'Made-ground soils' and 'Man-modified soils'. Aspects of the genesis and lithological character of Made-ground soils are analogous to anthropogenic deposits. They are formed through the mechanical removal, transport and deposition of man-made materials, natural pedogenic soils or natural geological parent material. Hollis (1992) proposed groups of 'man-made substrates' on the basis of their distinctiveness as anthropogenic artefacts within pedogenic soils, indicating whether they are chemically base-rich or base-poor reflecting their likely environmental impact. Although existing classifications or anthropogenic soils do not lend themselves to stratigraphy, they may provide useful markers in establishing a lithostratigraphy for artificial ground.

Topographical surveys. Topographical surveys with sequential generations of map information provide spatial information about types of artificial ground, ranging from many kinds of excavations and quarries through to engineered and tipped deposits. Maps show the locations and extent of built infrastructure including cuttings and embankments for castles, roads, railways, canals and docks. They show worked ground (quarries) mine and quarry waste (spoil tips), and other land-raising ground areas including waste disposal sites. Used in conjunction with other historical documents they can allow the genesis, and spatial and temporal distribution of some anthropogenic deposits to be delineated. Except for inference from certain types of mineral-processing spoil (i.e. coal or ironstone spoil tips), they provide little lithology information. Hence, topographical surveys offer a useful source of direct and indirect evidence to support the morpho- chrono- and lithostratigraphical classification of artificial ground.

National Land Use Database (NLUD) and Eurostat Land Use/Land Cover Area Frame Statistical Survey (LUCAS) classifications. The National Land Use Database (NLUD) is applicable to England, and characterizes the land into digital map-based polygons dependent on land use (Harrison 2006). Eurostat Land Use/Land Cover Area Frame Statistical Survey (LUCAS) classification is a similar European scheme, but with different subdivisions (Eurostat 2009). Both schemes divide the data into a two-tier hierarchy of Land Use and Land Cover, but have slightly different categories and subdivisions. Both include natural and agricultural land, along with categories for minerals and landfill or waste, transport, industrial and commercial land. Land-use classifications do not indicate the presence of artificial ground as such. Hence, land-use classifications could be of use in identifying areas of anthropogenic deposits, but, in general, do not help with their geological classification. The previous English scheme, called the National Land Use Classification (NLUC), was far more extensive and 'Although it has not been kept up to date, it arguably remains the most complete and detailed presentation of a nationally applicable land use classification' (Harrison 2006, p. 9). Elements of this extensive scheme could be used for subdividing some types of artificial ground, especially those associated with landscaped ground.

English Heritage *Thesaurus of Monument Types.* The *Thesaurus of Monument Types* includes hierarchical groupings and names for many types of building, archaeological structure, modern structure, mineral extraction sites, amongst others (English Heritage 2002). Ford *et al.* (2010*a*) suggested the use of this scheme for recording detail of artificial ground including earthworks and other constructions associated with archaeological sites.

However, it is debateable whether a geological recording scheme needs to subdivide to the same degree as the English Heritage scheme.

The applicability of lithostratigraphy to anthropogenic deposits

Lithostratigraphical procedure is essentially concerned with establishing the classification of rock bodies so that their geometrical shape and spatial relationships can be determined (Rawson *et al.* 2002). Lithostratigraphical units include bodies of sediment (or volcanic material), bedded or unbedded, that are defined and characterized on the basis of their lithological properties and their stratigraphical relationships (Salvador 1994). Globally, lithostratigraphical schemes have been systematically developed to facilitate the study, mapping and 3D geological modelling of bedrock and natural superficial deposits. However, no equivalent scheme exists for the characterization of anthropogenic deposits.

Potential difficulties in applying a lithostratigraphical scheme to anthropogenic deposits have, to some extent, already been faced for onshore natural superficial deposits (McMillan *et al.* 2005, 2011). Like natural superficial deposits, anthropogenic deposits are associated with a wide range of processes, they are commonly discontinuous, variable in thickness and poorly exposed. Furthermore, the regional significance of unconformities and discontinuities seen in sections or boreholes may be poorly understood. It is common that only a single thin unit is present and the deposits do not form a continuous stratigraphical succession. National or regional correlation may not be possible, and the definition of formations may be restricted to districts where correlation is secure. In the latter case, specific provisions have been necessary to account for the challenges associated with natural superficial deposits.

Notwithstanding these difficulties, lithostratigraphy provides an effective means of representing bedrock and natural superficial deposits, allowing different facies and phases of deposition to be represented at any one location and the geological history to be defined. Below, the applicability of lithostratigraphy to anthropogenic deposits is explored.

Lithostratigraphical procedures

If a lithostratigraphical framework is to be established for anthropogenic deposits it needs to conform, as far as possible, to international stratigraphical principles for lithostratigraphical classification (Salvador 1994). Regional application of these guidelines is published by the North American Commission on Stratigraphic Nomenclature (2005), and for Great Britain, most recently, by Rawson *et al.* (2002). The key requirements for a lithostratigraphical framework are:

- *Law of Superposition*: lithostratigraphical units are sedimentary (or volcanic) units that conform to the Law (or Principle) of Superposition, in that an undeformed succession is mainly deposited as layers with each layer younger than the one present beneath.
- *Original lateral continuity*: lithostratigraphical units should have, or originally have had, lateral continuity appropriate to the scale at which they are defined.
- *Lithological distinction*: lithostratigraphical units defined at the mappable scale should have distinguishing lithological characteristics that allow adjacent units to be differentiated. Units need not be lithologically homogeneous, although any variation should be described.
- *Type section*: a lithostratigraphical unit is defined by a type section (stratotype) or by type area. Where possible, the top and base should be defined, but it is recognized that the nature of these boundaries and the bounding deposits may vary laterally.
- *Hierarchical framework*: lithostratigraphical procedure is based on a hierarchical framework in which the 'Formation' is the primary mappable unit. Formations can be amalgamated into 'Groups', and then into 'Supergroups' or subdivided into 'Members', and then into 'Beds'.

Anthropogenic sediments and the Law of Superposition

The vast majority of anthropogenic deposits are formed by human processes that operate on the pre-existing landscape, including the gradual accumulation of material through settlement, industrialization, urbanization and waste disposal. Although evidence exists for submarine deposition (e.g. through the disposal of ship ballast: Boyce *et al.* 2009), anthropogenic sediments are most commonly deposited in terrestrial, subaerial environments.

Anthropogenic sediments may overlie earlier natural or anthropogenic deposits. In common with natural sedimentary deposits, they tend to form by aggradation at their upper bounding surface with successive layers representing younger depositional events (Fig. 5). Although the original lateral continuity, thickness and lithology of these layers may be characteristically different to those of natural sediments (as discussed in the following sections), they conform to the Law of Superposition. This axiom is a basis of archaeological recording and

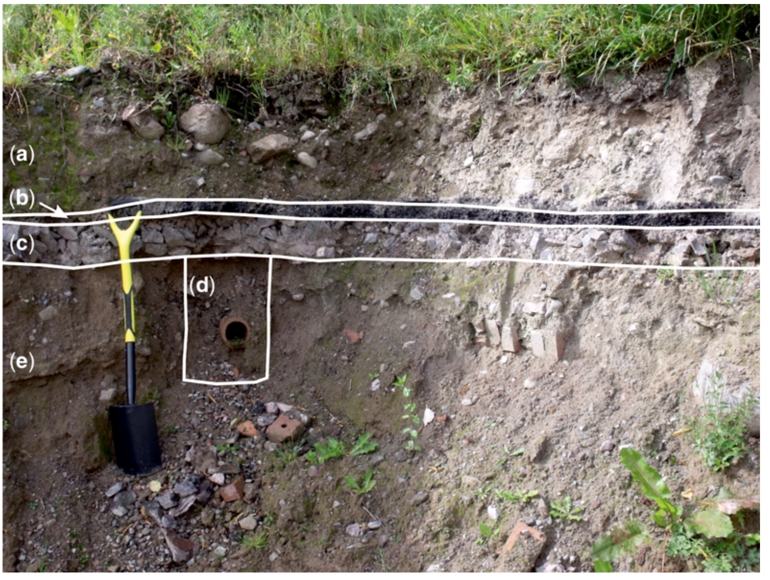

Fig. 5. Section through multiple layers of artificial ground showing superpositional and cross-cutting relationships analogous to those of natural sedimentary deposits. Units (a) and (e) comprise reworked, gravelly and cobbly silt and clay (till), unit (b) is tarmacadam, unit (c) comprises angular cobbles of concrete. Unit (e) is cut by a unit (d) and comprises reworked till used as back-fill for the installation of a clay pipe drain. Inverness area, UK [264135 844495]. Photograph by C. Auton BGS ©NERC 2012. All rights reserved.

interpretation, and is supported by a range of evidence including absolute and relative dating (see Edgeworth 2013).

Although multiple phases of anthropogenic deposition may be emplaced on a common surface, successive phases are often separated by periods of non-deposition, erosion (including excavation and natural down-cutting) and reworking. Although multiple units of anthropogenic deposit may be present at any single location, the preservation of complete or partial stratigraphical sequences is unlikely. The fragmented nature of anthropogenic sedimentary sequences presents a particular challenge to lithostratigraphical classification. Where evidence for relative field relationships is lacking, establishing the spatial relationships between deposits may require the use of chronostratigraphical or documentary evidence, including topographical and land-use information. Where natural and novel sedimentary environments interact, the stratigraphy of any intercalated or bounding natural deposits could be used to constrain the spatial relationships of the corresponding anthropogenic deposits.

The synsedimentary evolution of depositional environments may result in the distinguishing lithology or lithofacies of a single lithostratigraphical unit being deposited at different times across a sedimentary basin. Consequently, natural lithostratigraphical units commonly cut across time planes and boundaries defined by other stratigraphical classifications, including chronostratigraphy and allostratigraphy. Although regional unconformities or major hiatuses are used to separate lithostratigraphical units, local or minor hiatuses, disconformities or unconformities within a sequence are typically ignored (Murphy & Salvador 1999). By their nature, many anthropogenic units are strictly allostratigraphical: individual anthropogenic deposits are typically created in a single phase of deposition and their bounding surfaces, including local hiatuses and disconformities, *are* significant to their definition and identification.

With the exception of reworking and slumping (including the failure of engineered slopes in made ground), few immediate processes are likely to significantly disrupt the original superpositional nature of anthropogenic sediments. However, not all anthropogenic deposits conform to the Law of Superposition. Anthropogenic deposits created in the subsurface through activities such as mining, tunnelling and subsequent back-filling (Figs 5 & 6), or deposits resulting from the transfer of man-made materials into subsurface for storage or disposal, may exhibit complex relationships similar to natural intrusive rocks. By analogy, 'anthropogenic intrusives' that do not conform to the Law of Superposition may be described as lithodemic, and delimited on the basis of their rock characteristics

(Rawson *et al.* 2002). Such deposits may be hosted by earlier natural or anthropogenic deposits.

In modern urban environments, the anthropogenic impact in the subsurface due to the emplacement of material and the construction of foundations and infrastructure may be complex and extensive. This effect on the subsurface may be considered as a form of anthropogenic bioturbation or anthroturbation. Removed from the immediate effects of weathering and constant human reworking, the preservation potential of anthropogenic deposits emplaced in the subsurface may be greater than that of deposits created at the surface. The subsurface environment will be relied upon for a range of resources and services (including physical and thermal resources, space provision and storage), increasing the scale of anthropogenic intervention in the subsurface. This is likely to impart an anthropogenic signature on the subsurface that is characteristic of the proposed new epoch of time, the Anthropocene.

Original lateral continuity of anthropogenic deposits

Lateral continuity is a defining characteristic of lithostratigraphical units and their boundaries (Murphy & Salvador 1999). In the case of bedrock and, to a lesser extent, natural superficial sediments, depositional environments are typically widespread and bounded by physical limits including topographical barriers. The original lateral continuity of natural deposits may be interrupted by subsequent deformation or erosion associated with younger depositional events or topographical incision. However, individual units may commonly be traced over considerable ranges. Conversely, anthropogenic deposits are created in novel sedimentary environments that may be controlled by a combination of human factors in addition to physical constraints. These factors, including social and economic decision making, typically result in anthropogenic deposits that are discrete bodies with complex and largely unpredictable geometries. Deposits of similar character may coalesce to form composite units, or remain isolated but be considered as lateral equivalents. However, few individual anthropogenic deposits have the widespread lateral continuity that typifies and defines most natural lithostratigraphical units. To investigate the applicability of lithostratigraphy to anthropogenic deposits, the extent of natural and anthropogenic deposits can be compared.

Spatial extent of anthropogenic deposits. Based on BGS 1:50 000 scale geological map data of Great Britain, the largest contiguous area of a single bedrock formation (at rockhead) exceeds

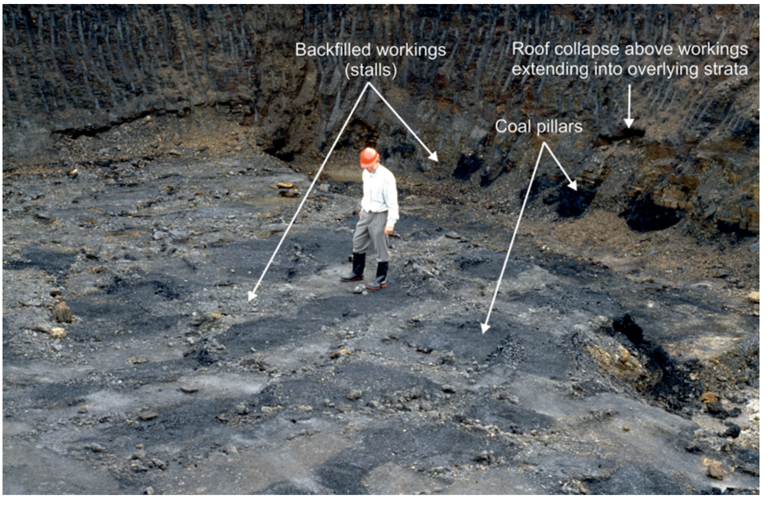

Fig. 6. Photograph showing back-filled underground mine workings, exposed by subsequent opencast mining. The remnant pillars of coal are evident as darker areas on the floor of the pit and lowermost part of the quarry face. The intervening stalls represent areas of mainly shale debris partly packed into the voids created by working the coal to help support the workings (often referred to as 'gob' or 'goaf') or the product of roof collapse. An area of such collapse, forming a choked chimney in the right of the photograph, extends about 1 m above the level of the worked coal. Materials emplaced in the subsurface by human processes may be considered as anthropogenic intrusive deposits. The disruption of the subsurface by human activities, such as underground mining and collapse, is described as anthroturbation. Dog and Gun Clay Pit [SE 053 344], Bradford, West Yorkshire. Photograph by C. N. Waters BGS

4600 km^2 (London Clay Formation in the Thames Basin). For natural superficial deposits, the equivalent (at outcrop) is around 2100 km^2 (till of the Lowestoft Formation in eastern England). In contrast, the largest area of artificial deposits (i.e. made or infilled ground) mapped at the same scale is 65 km^2, relating to made ground associated with the industrial legacy of Wolverhampton, central England. Made and infilled ground are typically an amalgamation of different deposits, and may be considered equivalent to group level in natural superficial or bedrock lithostratigraphy. In comparison to the mapping of natural deposits, that of artificial ground in Great Britain is relatively immature. This is reflected in the variable consistency and coverage of artificial ground data (Fig. 3). The map data for Wolverhampton are modern and many of the artificial deposits, including mineral spoil, are characterized by well-defined and readily mappable landforms. In other areas where the land-use history has resulted in extensive artificial deposits with little topographical expression, conventional mapping has often failed to depict these. This is particularly apparent in urban areas, including London, where unmapped artificial deposits are known from borehole records to blanket large areas.

At the other extreme, and perhaps more significant when considering the lithostratigraphical classification of anthropogenic deposits, named formations have been defined for bedrock deposits where the largest contiguous area (at rockhead) approximates to less than 0.007 km^2 (e.g. the Swindale Limestone Formation in NW England), and 0.003 km^2 (at outcrop) for natural superficial deposits (e.g. the Benholm Clay Formation of eastern Scotland). By comparison, the average area of artificial deposits is 0.07 km^2 in extent. For the natural deposits, these are the smallest extremes that have been mapped. They may arguably be seen as either excessive subdivision not representing the 'best practice' application of lithostratigraphical procedure, or they may be records detailing outcrops of unique local deposits.

Thickness and volume of anthropogenic deposits. Lithostratigraphical formations defined for natural deposits generally vary in maximum thickness from a few metres to several hundred metres (Rawson *et al.* 2002). The Lexicon of Named Rock Units (British Geological Survey 2012*a*) contains descriptions, including maximum thickness, of lithostratigraphical units shown on BGS maps. For formation-level lithostratigraphical units recorded in the Lexicon, the maximum thickness for superficial deposits ranges from around 0.7 to over 80 m (averaging 15 m), and around 5 m to over 2 km for bedrock units (averaging 400 m). Greater maximum thicknesses are recorded for bedrock units where tectonic thickening is suspected. The *Lexicon of Named Rock Units* is mainly lithostratigraphical, but it incorporates morphostratigraphical (and lithodemic) schemes, including the BGS artificial ground classifications. However, no information is given for the thickness of anthropogenic deposits.

Borehole records are commonly used in mapping and 3D geological modelling, and offer additional information including the thickness of anthropogenic deposits. The UK National Geoscience Data Centre's collection of onshore boreholes and trial pit records includes over 1.3 million entries (British Geological Survey 2012*b*). The distribution of boreholes and trial pits is generally concentrated in urban areas and centres of extractive industry. About 10% of registered boreholes and trial pits intersect categories of artificial ground on BGS 1:50 000 scale maps that are likely to include anthropogenic deposits. Although many records predate development activities (e.g. construction) that can result in subsequent creation of artificial ground, they provide useful information on the thickness and spatial extent of pre-existing anthropogenic deposits. The greatest intersections of anthropogenic deposits proved in boreholes are typically associated with infilled ground and, specifically, the use of man-made excavations for waste disposal. For example, an intersection in excess of 65 m of back-filled opencast colliery spoil is recorded in the Leeds area of northern England, and is considered to be towards the upper limit of thickness for anthropogenic deposits in Great Britain. Borehole records indicate that these deposits represent a single phase of deposition with a definable lithological character, and may be considered as a single anthropogenic unit. Compaction and diagenesis may reduce the thickness of these deposits, but, if preserved in the rock record, they would present a mappable unit similar in thickness to many natural deposits.

Deeper excavations are recorded in Great Britain, including many that are wholly or partially infilled. However, information on the thickness and lithology of any fill is limited by the age and distribution of borehole records or other evidence. Significant thicknesses of anthropogenic deposits are also likely in the case of back-filled shafts and wells; however, these types of deposit may be more appropriately characterized as anthroturbation or anthropogenic intrusive and subject to lithodemic classification (see the earlier subsection on 'Anthropogenic sediments and the Law of Superposition').

In general, artificial ground is included on BGS 1:10 000 scale maps where the maximum thickness, or depth, is interpreted to be greater than 1 m, based

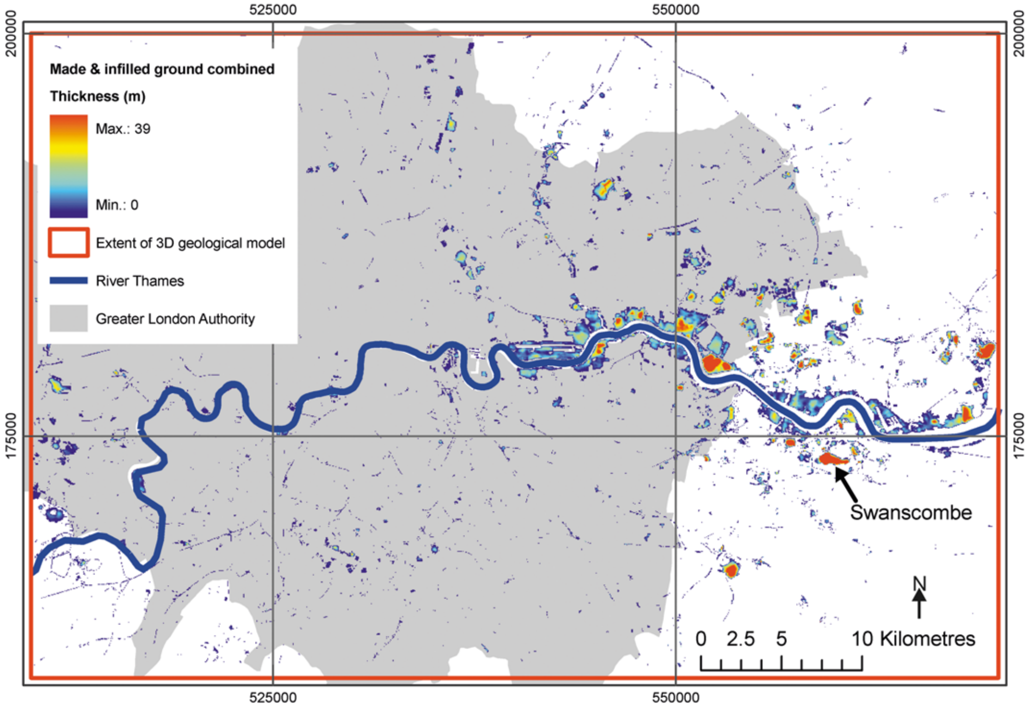

Fig. 7. Map showing the thickness and distribution of artificial ground in the London area based on a 1:50 000 scale 3D geological model (Ford *et al.* 2010*b*). Greater London Authority boundary and River Thames included for reference. Infilled chalk quarries in the Swanscombe area, east of London, show the greatest thickness of anthropogenic deposits.

on landform or borehole evidence. Although geological maps typically give no indication of thickness range, this information can be determined from 3D geological models of the shallow subsurface. For example, the 1:50 000 scale 3D geological model of London (Ford *et al.* 2010*b*) includes major areas of artificial ground (Fig. 7). The greatest concentrations are located in the east of the city and adjacent to the River Thames. An estimate for the mean thickness of undifferentiated anthropogenic deposits based on the model is 1.6 m, reaching a maximum of 39 m in the Swanscombe area of east London where the landscape has been subjected to extensive quarrying of the chalk bedrock and subsequent infilling with material including overburden.

The maximum thickness of anthropogenic deposits is comparable to those derived from the model for natural superficial and bedrock formations including, for example, Pleistocene river terrace deposits (Taplow Gravel Formation, subsequently reclassified as a member in the Maidenhead Formation by McMillan *et al.* 2011) and Palaeogene marine sands (Thanet Sand Formation) (see Table 1). Similarly, the mean thickness of anthropogenic deposits is comparable with the range shown for natural deposits. However, the thickness distribution of anthropogenic deposits differs considerably, being strongly skewed towards lower values (Fig. 8). Almost 90% of the anthropogenic deposits are less than 3 m thick, compared to 6 m for the Taplow Gravel Formation and 20 m for the Thanet Sand Formation. This bias towards relatively thin and discontinuous deposits represents a key challenge in defining a lithostratigraphical classification for anthropogenic deposits.

Three-dimensional geological models allow volumes of material to be assessed. The 1:50 000 scale model indicates that the volume of anthropogenic deposits in London is 168×10^6 m^3. This model excludes deposits of less than 1 m in maximum thickness, including many related to road construction, shallow foundations and landscaping. These deposits may be ubiquitous across much of the Greater London Area (Fig. 7), requiring an average thickness of only 0.1 m across the area to match the figure of 168×10^6 m^3. The spatial characteristics of anthropogenic deposits in London are likely to be representative of other areas with broadly similar economic and social history.

Table 1. *Summary showing thickness information for anthropogenic deposits, and selected examples of natural superficial and bedrock formations in the London area based on 3D geological modelling (Ford* et al. *2010b)*

Unit type	Unit name	Maximum thickness (m)	Mean thickness (m)	Standard deviation	90th percentile	Volume (km^3)
Anthropogenic	Made ground	26	1.4	2.6	–	0.10
	Infilled ground	39	2	3.8	–	0.07
	Made and infilled ground combined	**39**	**1.6**	**3.05**	**3**	**0.17**
Natural superficial	**Taplow Gravel Formation***	**15**	**3.7**	**2.5**	**6**	**0.55**
Bedrock	**Thanet Formation**	**50**	**12.8**	**6.4**	**20**	**22.17**

*Taplow Gravel Formation, subsequently reclassified as a member in the Maidenhead Formation by McMillan *et al.* (2011). The distribution of thicknesses for the units shown in bold are compared in Figure 8.

Temporal changes in volume and extent of anthropogenic deposits. Globally, changes in technology over time have had a dramatic influence on the extent and thickness of anthropogenic deposits. For example, early mining was undertaken largely by hand, but, as steam- and then oil-powered machines were introduced, far greater volumes of anthropogenic sediment could be moved and significantly greater anthropogenic deposits created. In coal-mining areas, increased ratios of coal to overburden are reflected in the size and thickness of associated anthropogenic deposits, including spoil heaps. In Great Britain, ratios of coal to overburden changed from around 1:3 during the early 1940s to 1:18 in 1999 (International Mining Consultants Limited 1999). Similarly, average ratios in US mines changed from around 1:6 to 1:11 between 1946 and 1970 (Boudette *et al.* 1976), and in eastern US mines the ratio changed to between 1:15 and 1:25 by 2002 (US Environmental Protection Agency 2002). Ratios of waste to product for coal, iron ore, most metalliferous and many non-metalliferous minerals have all seen a dramatic rise since World War II. In fact, since 1945, mineral output and related waste production has risen to about 45 km^3 per year, a trend that continues. Similarly, the volume of material excavated and used for major constructions has increased dramatically, driven by widespread land reclamation and infrastructure construction. World cement and aggregate production has followed a similar trajectory to mineral production. Records suggest that around 40 km^3 of limestone, shale and aggregate are currently excavated and moved each year. The total volume of anthropogenic deposits resulting from earthworks will be considerably greater than the volume of construction materials.

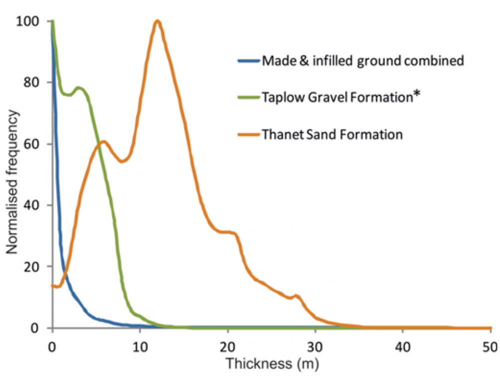

Fig. 8. Chart comparing the thickness distribution of anthropogenic sediments with natural superficial and bedrock units in the London area based on 3D geological modelling (Ford *et al.* 2010*b*). Frequency is normalized to 100 for each unit. *Taplow Gravel Formation, subsequently reclassified as a member in the Maidenhead Formation by McMillan *et al.* (2011).

Along with temporal changes in the volume of other sources of anthropogenic sediment, including landfill waste, changes in the spatial extent of anthropogenic deposits through time may offer a distinguishing characteristic to support the application of lithostratigraphy to anthropogenic deposits. However, on a regional, or even national, scale, significant changes in the volume and extent of anthropogenic deposits may be highly diachronous. The onset of major urban and industrial expansion in Great Britain that resulted in a significant increase in the scale of anthropogenic deposits began around 1750 at the time of the Industrial Revolution. Significant expansions are only now being experienced by some emerging economies of the developing world. Similarly, ancient civilizations across many continents have been responsible for the creation of considerable anthropogenic deposits many millennia before the Industrial Revolution in Great Britain (e.g. Edgeworth 2013).

Lithological distinction of anthropogenic deposits

Establishing a lithological distinction between adjacent units based on observable characteristics is an essential criterion in lithostratigraphical classification. As analogues for natural sediments, anthropogenic deposits exhibit lithological characteristics, and can largely be described in conventional terms including composition, grain size and texture. Anthropogenic deposits may exhibit considerable lateral and vertical lithological variation. Distinguishing characteristics should be apparent at the mappable scale in outcrop, in hand or core samples, or with low-magnification microscopy. Whilst natural exposures of anthropogenic deposits are relatively rare, temporary excavations and trial pits or boreholes for ground investigation can reveal their presence and composition.

Composition of anthropogenic deposits. The bulk composition of anthropogenic deposits may be considered in terms of three components: (1) anthropogenically redeposited or disturbed natural materials that have undergone little or no processing; (2) natural materials deposited from natural or indirectly modified sedimentary systems; and (3) novel materials of an entirely artificial origin that have been processed or manufactured and commonly subjected to heat and/or pressure. A dominant proportion of redeposited or novel material in the bulk composition of a deposit may be definitive of an anthropogenic deposit (Fig. 1b).

Redeposited natural geological materials may be locally derived; for example, in the case of construction site formation where excavated natural material is used nearby as fill. When processing is limited, the composition of the resulting anthropogenic deposit will broadly reflect that of the natural source material. However, the anthropogenic deposit may be distinguished from the parent geological material by the disturbed fabric of the sediment, weathering characteristics and the presence of exotic anthropogenic components (including novel materials) incorporated through mixing. Where multiple phases constructed of locally derived deposit are juxtaposed, the distinction between units on lithological character alone may be problematic.

Redeposited natural geological materials may also be sourced from outside the immediate area in response to economic factors, locally unobtainable quantities or the requirement for material with particular physical characteristics, such as permeability or strength. Imported material is likely to be compositionally distinct from locally occurring natural deposits. For imported natural materials, extensive source areas (or catchments) may result in anthropogenic deposits that are compositionally diverse and readily distinguishable from one another, even where their end use is comparable. However, where restricted or established supply areas exist for particular materials (e.g. major quarries or sand and gravel production areas), multiple phases of deposition may exploit the same parent material and result in sediments that are essentially similar in composition. The transfer through time of sediment supply between source areas as resources are exhausted or new production is introduced may leave a distinct signal in the record of anthropogenic deposits. This is analogous to natural systems where unroofing of a buoyant lithosphere can produce sediment of progressively deeper source being transported into a nearby depositional area.

Novel materials of an entirely artificial origin represent a significant component of many anthropogenic sediments. Volumetrically, the most significant novel materials are glass, plastics, ceramics, concrete, brick and smelting slag (Zalasiewicz *et al.* 2011). Many novel materials are themselves composed of, or derived from, original natural rock, superficial deposits or fluids extracted from the ground. However, their distinguishing feature is that they have been processed, manufactured or refined by human activity in some way to change their original physical and chemical structure. They may have undergone mixing, been chemically formed or, more commonly, altered through being subjected to heat.

Novel materials may occur as component parts of relatively homogenous packages of sediment related to a single, dominant land use (e.g. ceramic waste tips in Great Britain: Wilson *et al.* 1992), or in mixed anthropogenic sediments, or in naturally occurring sediments that have been reworked (Fig. 9). The latter are common where land has been subject to successive phases of use for different purposes. Norbury (2010) recognized that some types of novel materials are strongly related to their geographical and geological location and setting; for example, ‘blaes’ is a distinctive orange gravel arising from the production of paraffin from combusted oil shale in Scotland, and is commonly used as subgrade for road construction in the area.

Where novel materials are present, the distinction between anthropogenic and natural sediments is generally straightforward. Novel materials may be recognized by characteristics including composition, shape and size of grains, colour and markings. However, novel materials, including plastics, bricks and metal are increasingly present in the natural sedimentary cycle, carried by river systems and incorporated into a range of natural deposits that may subsequently be redeposited as anthropogenic sediments (Fig. 9). Natural materials deposited in modified natural situations include sediments deposited in artificially dammed valleys.

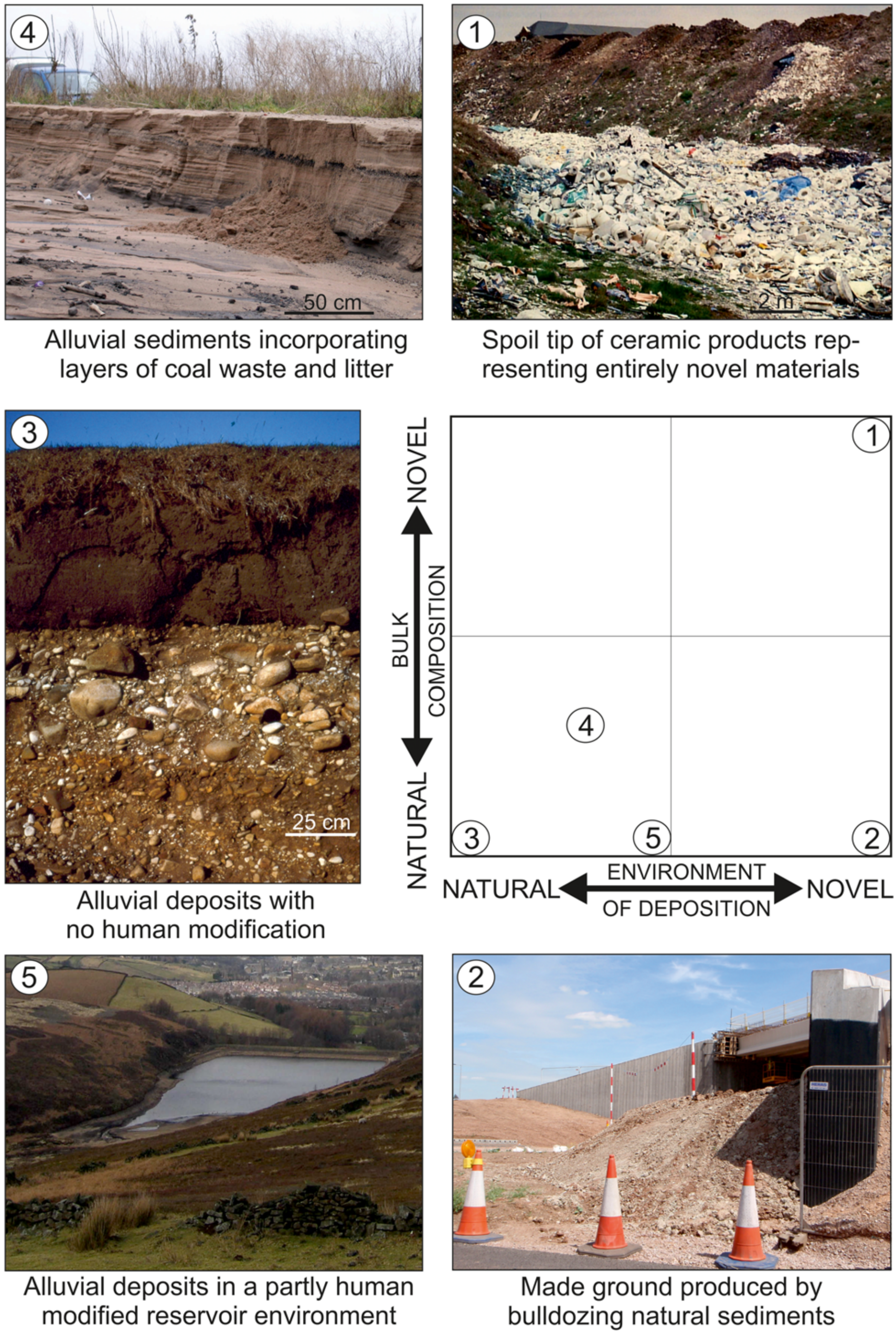

Fig. 9. Relationship between the environment of deposition and bulk composition of sediments including anthropogenic deposits. The range of possible combinations of environment and composition highlights the diverse and extensive nature of deposits that may contribute to the definition of the Anthropocene. The anthropogenic deposits shown in Figures 12 & 13 would plot in similar positions to (1) and (2) respectively. Photography by BGS ©NERC 2012. All rights reserved.

As such, the sediments will be similar to other natural sediments in lithology, texture and grain size, but the geological setting will be modified, and sequences such as those found in deltas and lakes may form in dammed valleys.

Reworking of anthropogenic sediments is widespread in the urban environment and presents a challenge to establishing a lithological distinction between adjacent units. The reuse and redevelopment of land, and the recycling of materials on a site-, local- and regional-scale (the latter now common practice in the construction industry), results in extensive deposits of derived anthropogenic sediment, including novel materials and human-made components. Reworking can result in the homogenization of anthropogenic sediment that may originally have represented multiple phases of deposition. Where natural sediments have been reworked and deposited forming a new structure for an engineering purpose, sediments are likely to be more homogenous than those deposited without engineering control. The extent of reworking in the novel sedimentary environment is arguably much greater than in most natural sedimentary environments. Although documentary evidence (e.g. historical maps) may indicate the reworked nature of anthropogenic sediments, observable characteristics that may allow reworking of natural sediments to be recognized (e.g. disturbed or reorientated fabric) are not generally meaningful for anthropogenic sediments.

Temporal changes in the composition of anthropogenic deposits, including waste. The presence of novel materials in artificial sediments will generally aid the distinction between adjacent units and may represent the defining factor where natural components are not diagnostic; for example, in the case of locally sourced, redeposited natural geological materials. Inevitably, some novel materials become obsolete with time and their relative abundance or assemblages my provide markers for units of a particular age, in a way similar to fossils in the biostratigraphical classification of natural deposits (Fig. 10).

The definition of a lithostratigraphical unit should be based upon the nature of the deposits and can be independent of time constraints. Hence, should a decision be made to define a new Anthropocene Epoch (e.g. at the incoming of plastics around 1950), some units of artificial deposits that are defined lithostratigraphically would be Anthropocene in age, others would span the boundary with the Holocene, many would be entirely Holocene in age. However, the lithological composition of anthropogenic deposits may be influenced by a combination of factors, including technological, societal and economic drivers, and therefore be strongly indicative of their age. Major historical events including conflict and advances in technology have resulted in discernible changes to the composition of anthropogenic deposits. For example, changing practices in methods for the extraction of coal have resulted in not only a rapid increase in the volume of spoil produced, but also the proportions of coal to waste in spoil tips have typically decreased (Waters *et al.* 1996). Understanding temporal changes in composition may support the application of lithostratigraphy to anthropogenic deposits and contribute to the definition of the Anthropocene.

In Great Britain, the transformation from a nomadic hunter–gatherer society to one of settlement, farming and agriculture is associated with the Neolithic (*c.* 4000–2600 BCE). During this time, the scale of direct human transformation of the landscape and the creation of novel sediments was limited by population, availability of raw materials, technology and economic growth. However, localized extraction and processing of metals and subsurface resource exploitation was present on a site scale (Price *et al.* 2011). Settlement and growth of towns following the Roman occupation of Great Britain was associated with an increase in the use of geological materials for construction and engineering, including raw materials for bricks and mortar, crushed rock, dimension stone and roofing slates. It is these materials that form the pre-industrial anthropogenic deposits that are often recognized in the archaeological record, buried beneath the foundations of modern towns and cities. Correspondingly, the pits and quarries used to source these materials may still be evident, partially or wholly back-filled with later anthropogenic deposits.

Pre-industrial Great Britain prior to the eighteenth century was, therefore, largely dominated by exploitation and the use of natural geological materials in construction and engineering as towns began to develop, and people settled in one place. The onset of the Industrial Revolution marked a rapid increase in the rate of exploitation and use of geological materials for construction and engineering, including the placement of these materials in the subsurface as sewerage and underground transport networks were developed. Technological innovation and development, fuelled by coal, resulted in ever-deeper levels of anthroturbation to exploit coal and mineral resources. Subsurface anthropogenic deposits in the form of mineral waste 'goaf' were deposited (Fig. 6), in addition to the creation of voids through shafts, adits and working levels in mines. The deposition of anthropogenic deposits and mineral spoil above ground was common, and often widespread. Manufacturing and processing of iron ore and other metals to provide the raw

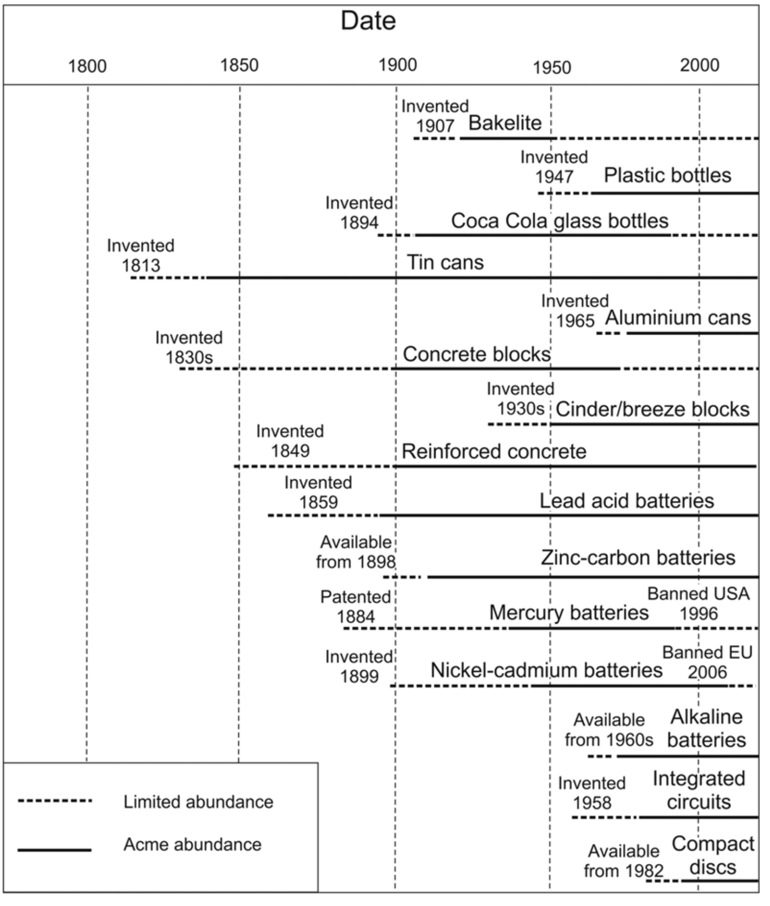

Fig. 10. The first appearance and acme of selected novel materials post-1800 that may, by association, allow the relative age of anthropogenic waste deposits to be determined. The ranges are schematic, based on European/North American landfill deposits, and do not consider global diachroneity.

materials for buildings, machinery and transport infrastructure became widespread. Cities grew as the urban population expanded.

The Industrial Revolution marked a change in the character of anthropogenic sediment deposition in four main ways of potential lithostratigraphical significance. First, the rate of production and use of building and construction materials including bricks and mortar, dimension stone and glass increased. Second, the exploitation of subsurface resources increased and deposition of associated surficial waste tips became widespread. Third, the extraction, processing and use of metals in buildings, transport infrastructure and in manufactured goods increased dramatically, resulting in a significant rise in the proportion and widespread occurrence in the sedimentary environment of novel anthropogenic materials including processed metals and manufactured goods. Fourth, with the increasing exploitation of deeply buried mineral resources, installation of underground transport and drainage infrastructure, anthropogenic materials were commonly deposited below the ground. Arguably, these changes mark the beginning of the acme of anthropogenic deposition.

Subsequent post-industrial development saw rapid population growth increasingly concentrated in towns and cities. In western Europe, this growth and development was disrupted by the outbreak of two world wars. Many cities were partially destroyed as a result. In many cases, building rubble resulting from war damage was widespread and commonly used as fill or, even, ship ballast (Thorpe *et al.* 2011).

The period following World War II in western Europe saw an acceleration in urban growth, technological innovation and increasing use of geological materials. This innovation led to the manufacture and use of a variety of new and novel anthropogenic materials. Oil exploitation and refining produced the feedstock to make many petroleum derivatives such as plastics. The use and implementation of electronic technology expanded, including computers for industrial and personal use. Portable electronic devices including stereos, mobile phones and laptop computers required batteries. In construction, the post-war period saw an acceleration in the use of concrete and the exploitation of the raw material required for its manufacture. The post-war period therefore marks a time during which technological development and rapid urban growth provided the potential drivers and source materials for novel anthropogenic deposits characterized by electronic equipment, extensive concrete manufacture, deep mining and the generation of vast amounts of wastes.

Throughout human history, wastes, including mine spoil, industrial and domestic refuse, comprise the main types of anthropogenic deposit by volume. The lithological composition of waste deposits is largely defined by the source activity. However, other factors including prevailing legislation and the way in which wastes are managed and treated can influence their composition. Consequently, wastes are of particular significance to lithostratigraphical classification as they result in deposits with diverse and distinct lithological characteristics. In the case of municipal solid waste (MSW) deposited as landfill (including historical middens), compositions have changed considerably with time. For example, prior to 1800, volumes of waste in Great Britain were small and dominated by ash, wood, bone, and body and vegetable wastes, with a low proportion of metal due to reuse and recycling (Waste Online 2004). In the 1800s, waste volumes increased and compositions changed to include domestic, industrial, commercial, mine and quarry waste. By the early twentieth century, most houses were fuelled by coal fires, consigning significant volumes of ash to landfill. However, following the implementation of the Clean Air Act in 1956, the use of coal fires in homes, and the proportion of ash and cinder in landfill waste, began to decline (Fig. 11). In the 1960s, with burgeoning production of plastics to replace traditional materials and with increased consumerism and waste production, the volume and composition of wastes changed radically. Subsequent legislation, including the Control of Pollution Act in 1974, and increased reuse and recycling resulted in greater segregation of waste materials, and corresponding changes in waste volume and composition (European Union 1999, 2008). In 2006–2007, the composition of household waste in England included 23% paper and card, 18% food, 16% garden and other organic waste, 10% plastics, 6% glass, 4% metals, 4% wood, 3% textiles, 2% waste electrical and electronic equipment, and 14% 'other' including batteries and hazardous material (Department for Environment Food and Rural Affairs 2009).

In addition to diachroneity related to the volume and extent of anthropogenic deposits, compositional characteristics may also be expected to show contrasting rates of change on a regional and global scale. Whilst the bulk composition of anthropogenic deposits is likely to be most strongly influenced by local natural resources and remain relatively constant through time, aspects such as the specific types and proportion of novel materials may be indicative of an area's particular stage of societal or economic development. However, with increasing globalization in the modern era, the time gap and diachroneity associated with the proliferation of novel materials is, in many cases, considerably reduced.

Preservation potential of anthropogenic deposits. The relative preservation potential of materials comprising anthropogenic sediments, including novel materials and organic content, should be considered when comparing the composition of deposits. Notwithstanding destruction through physical erosion, preservation potential is largely a response of material composition to the physiochemistry of the environment of deposition. Significant environmental parameters that control preservation potential include moisture, temperature, redox potential and pH. For example, bricks may be susceptible to physical degradation in the presence of water and changes in temperature. Processed metals and alloys derived from iron ore are likely to corrode in the presence of oxygen and chloride ions. Plastics, representing synthesized polymers derived from hydrocarbons, may be subject to chemical and physical degradation when exposed to light, oxygen, heat or corrosive fluids. Much like archaeological residues, organic anthropogenic materials may decay after deposition unless they are deposited rapidly in an environment that favours their preservation. There are many cases of exceptional preservation of organic remains in waterlogged cultural deposits beneath cities including York and London in the UK (McCann & Orton 1989; Holden *et al.* 2009). In the case of modern municipal waste, it is estimated that 67% is biodegradable (Department for Environment Food and Rural Affairs 2009). This suggests that if all municipal waste were deposited in landfill, 33% would be available for long-term preservation. Many anthropogenic deposits comprise mixtures of geological raw materials that exhibit differing potentials for preservation. Concrete, for example, is commonly made from siliceous aggregate and cement. Silica

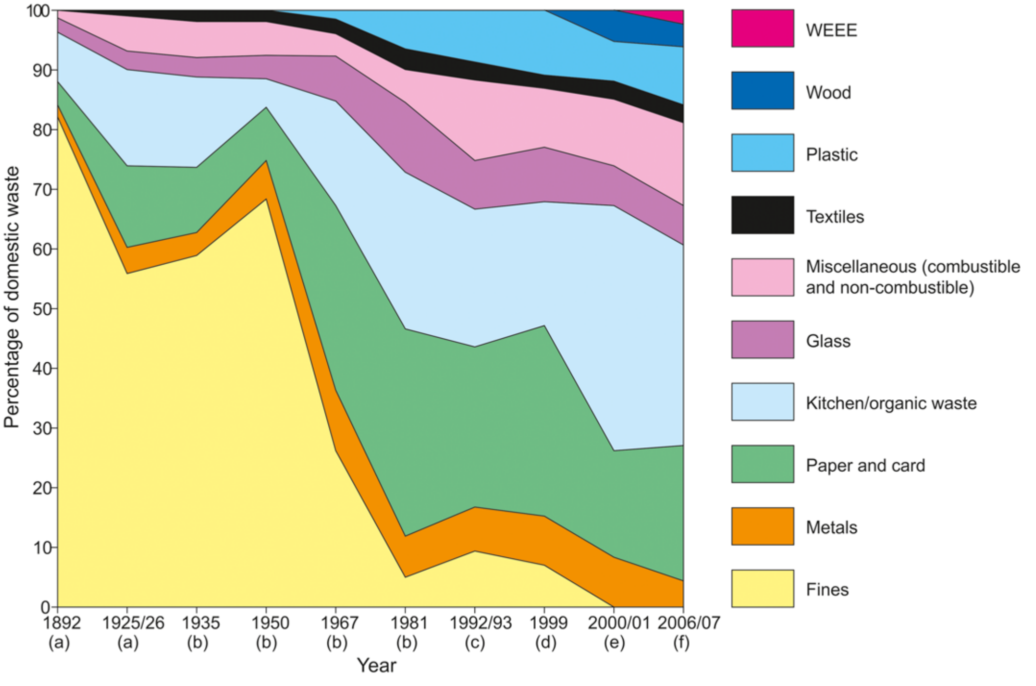

Fig. 11. The change in composition of household Municipal Solid Waste (MSW) in Great Britain. Percentage by weight measurements based on surveys of household collected waste only. The fines category includes dust, ash and undifferentiated screenings. WEEE (Waste Electrical and Electronic Equipment) may be reported in other categories prior to 2002. Based on and incorporating data from: (**a**) Waste Online (2004) and Gandy (1993); (**b**) Bridgewater (1986); (**c**) Burnley (2007), data collected from wheeled bins in England and Wales only; (**d**) Burnley 2001; (**e**) Parfitt (2002); and (**f**) Department for Environment, Food and Rural Affairs (2009), data from England only.

typically provides a robust, preservable material, but the concrete's matrix may be susceptible to chemical and physical degradation, especially in the presence of sulphate- or chloride-rich groundwaters. This change would be a form of diagenesis, equivalent to that seen in bedrock units, with resultant redeposition of calcium carbonate significantly modifying the porosity and permeability of the deposit.

The lithological characterization of anthropogenic deposits. In recognition of the specific engineering and environmental challenges posed by anthropogenic deposits, schemes have been developed for their lithological characterization, including those that make specific provision for novel materials and waste (Hollis 1992; Environment Agency 2005; Norbury 2010).

Norbury (2010) distinguishes three categories of man-made soils for engineering geological purposes which define the lithological composition of anthropogenic deposits:

- Those fine or coarse soils composed of natural materials that have been laid down (redeposited) by man to form new structures like embankments. It may not be easy to recognize such materials without considering other sources of information such as land use, landforms and historical maps.
- Those fine or coarse manufactured or processed materials laid down by man that can be described and tested geotechnically as they are physically or chemically similar to natural soils (e.g. washed materials such as mine tailings from non-coal mines, crushed rock back-fill).
- Those fine or coarse manufactured materials laid down by man that cannot be easily geotechnically described (e.g. domestic refuse in landfill, fly-tipped material and demolition rubble).

The two latter types include deposits that are composed completely or partially of anthropogenic material and may be mixed with reworked natural deposits derived from bedrock or unlithified superficial deposits.

In Great Britain, wastes are classified according to the List of Wastes Regulations 2005 (Environment Agency 2005), which provides codes for all hazardous and non-hazardous wastes based on the process that created them or the material type. It comprises 20 high-level categories of waste with further subdivisions, and includes over 1300 descriptions of common waste types.

The use of these schemes may complement conventional geological description in the lithological characterization of anthropogenic deposits for the purpose of defining lithostratigraphical units. They are applicable where anthropogenic deposits are relatively homogenous as a result of similar land-use processes or the degree of engineering control applied to their deposition. However, anthropogenic deposits are commonly characterized by mixtures of natural and anthropogenic material deposited by more than one type of process. Such processes can include multiple phases of land use during urban development, but it may not be possible to distinguish the individual stages that formed them. For the lithological characterization of artificial deposits that comprise mixtures of anthropogenic and natural materials, existing schemes used in isolation are unlikely to be effective.

Grain size of anthropogenic sediments. The component parts of anthropogenic sediments can be considered as clasts or grains, and their size, shape and sorting can be used to define the lithological character of anthropogenic deposits. Grains may be identified for novel, natural or reworked natural components. The grain size of reworked natural material may reflect the primary deposit; for example, in the case of unlithified gravel. However, where cohesive material including clay or rock is moved intact by mechanical excavation, individual pieces or blocks may be considered analogues to lithic clasts in natural sediments. In this case, the size of the clast, as well as the grain size of the primary material, may be described. Novel materials may be described in a similar fashion, with some materials representing grains of single composition and others representing composites.

The grain size of anthropogenic deposits can be classified by existing schemes that are commonly used to describe natural deposits (e.g. Wentworth 1922; British Standards Institution 1999). Such schemes classify grain size into primary classes of clay, silt, sand, gravel, cobble and boulder. Combinations of these classes can be used to describe sediments of mixed grain size.

For natural clastic sediments, grain size is controlled by factors including environment of deposition, distance travelled from the source area and the nature of the parent material. Sediment transported in many natural fluvial and aeolian environments results in a relatively high degree of sorting. Although manufacturing or processing techniques and the formation of tailings ponds can result in well–sorted anthropogenic sediments, typical transport methods are unlikely to significantly affect grain-size distribution. Consequently, anthropogenic sediments, especially those associated with waste deposits, are typically poorly sorted and exhibit large ranges in grain size, sharing similarities with natural 'boulder clay' or breccia deposits.

The inclusion of novel deposits in artificial ground may require the description of diverse lithologies that are present as clasts within a matrix of natural reworked or novel deposits. For example, demolition spoil may contain large boulders of reinforced concrete, and boulder-sized debris of wood, cobbles of brick and cement in a matrix of sand and gravel. Old landfill sites could include boulders of domestic appliances with cobbles of tins and glass, and plastic bottles plus gravel-sized batteries in a matrix of degraded cardboard and vegetable matter.

The use of lithological descriptors such as clay, sand and gravel has been used extensively within the classification scheme for natural Quaternary deposits (McMillan *et al.* 2011). However, inclusion of a lithological term is discouraged by Salvador (1994) and, because of the inherent heterogeneity of artificial deposits, would not be a suitable adjunct to a lithostratigraphical name.

Sedimentary textures and structures within anthropogenic sediments. Sedimentary structures and textures may be evident within anthropogenic deposits, sharing many common characteristics with natural deposits. They include bedding, lamination, graded-bedding and cross-bedding. The presence of sedimentary structures is controlled by the method of emplacement and the magnitude of subsequent reworking. For example, sedimentary structures such as cross-bedding and lamination can be formed during sedimentation in tailing ponds. Similar structures can also be formed by reworking and hydraulic pumping of sediment from shallow-marine environments onto land reclamation. Large-scale pseudo-cross-bedding can be formed by the tipping and gravitational sorting of materials such as mine waste on spoil heaps (Fig. 12). The way materials are engineered may result in internal sedimentary structures that are diagnostic of particular activities, with types of structure reflecting temporal changes in engineering practices such as old 'end-tipped' railway embankments with little compaction to modern emplaced and compacted road embankments. Similarly landfill sites may show mixed waste deposits that range from old end-tipped materials to modern tipped, spread, compacted and engineered sites formed in lined excavations and capped.

Figure 13 illustrates two examples of sedimentary structures observed during recent terrestrial

Fig. 12. Aerial photograph showing the geomorphology, process of deposition and sedimentary architecture of a westwards-prograding waste deposit in the NE of England. Waste slag from steel industry is initially deposited by trailer, then pushed up to the front of the deposit by bulldozer to form a series of west-facing ridges comparable in genesis with push-moraines and in overall geometry with natural sedimentary foresets. Aerial photography ©UKP/Getmapping Licence No. UKP2006/01.

landscaping and land reclamation between Dubai and Abu Dhabi in the United Arab Emirates.

Although material structures are not a defining characteristic in lithostratigraphical classification, they can complement lithology and field relationships in providing evidence to help distinguish otherwise similar units and to understand depositional history. As the nature and scale of anthropogenic deposition has changed with time so have the range of structures exhibited by these deposits.

The definition of type sections for anthropogenic deposits

The definition of lithostratigraphical units requires a type section or area to be designated. Type sections provide a formal reference, and should satisfy a range of criteria including being representative of the boundaries of a unit, its lithology or lithological range and, ideally, including a full thickness of the unit in an area where it is at its thickest development. Where these criteria cannot be met by a single type section, composite type sections or type areas may be defined. Type sections should be accessible and have a reasonable likelihood of long-term preservation (Salvador 1994; Rawson *et al.* 2002; North American Commission on Stratigraphic Nomenclature 2005).

As part of the definition of a stratotype, it is necessary to define the base and top of the unit. Where anthropogenic deposits rest directly on natural deposits, the lower bounding surface may be defined as an unconformity. This surface may be the natural land surface or a surface modified by human processes, including excavation. In Japan, the boundary between the artificial and natural deposits is termed the Jinji Unconformity (Nirei *et al.* 2012). In Great Britain, the term rockhead is used to describe the boundary between bedrock and overlying natural and anthropogenic superficial cover (Lawley & Garcia-Bajo 2009). Rockhead in areas of exclusively anthropogenic cover can be used to define the equivalent of the

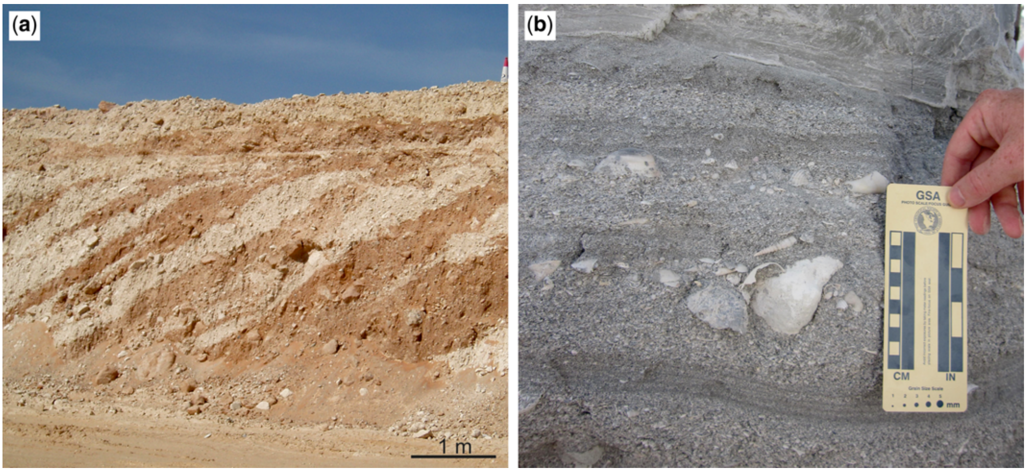

Fig. 13. (**a**) Photograph of anthropogenic deposits showing cross-stratification foresets produced through successive phases of bulldozing aeolian sand and angular fragments of calcareous sandstone during landscaping near Abu Dhabi, United Arab Emirates. Material has been pushed down to the front of the deposit, similar to the accretion of a prograding delta in natural sediments. (**b**) Photograph showing laminated anthropogenic deposits disturbed by the emplacement of an angular sandstone fragment in sediments deposited as slurry during land reclamation near Abu Dhabi, United Arab Emirates. Photographs by BGS ©NERC 2012. All rights reserved.

Jinji Unconformity. Although this unconformity should be readily recognizable, the identification of distinct and regionally correlatable discontinuities *within* artificial successions is more problematic, particularly as hiatuses may be sufficiently short not to be associated with soil development and have little lateral continuity.

In the cases where anthropogenic units are concealed, their upper and lower bounding surfaces may be erosive and characterized by complex cross-cutting relationships. This presents a particular challenge when defining a stratotype as complete sections may not exist, and establishing and correlating reference or composite sections may be complicated by the highly dissected nature of anthropogenic deposits.

In the case of natural deposits, a combination of exposed sections (natural and man-made) and borehole material is used to represent type sections. In some cases, type sections are actively managed to preserve their integrity and permit access (Ellis 2008). In the case of anthropogenic deposits, present-day natural exposures are rare. Exposures that develop naturally (e.g. flood events eroding embankments) or those created by man-made excavations will usually provide only temporary sections. Therefore, defining suitable type sections for anthropogenic deposits based on exposures is likely to be impracticable. Anthropogenic deposits are, however, commonly recovered in borehole samples during ground investigation, especially in areas of regeneration, and such material may offer the best opportunity to observe their lithological characteristics. However, as anthropogenic deposits are often loose or poorly compacted, they are rarely recovered intact and the nature of their bounding surfaces may be unclear. Also, borehole samples are rarely retained beyond the life of the ground investigation and, for the foreseeable future, available borehole material is unlikely to represent all anthropogenic deposits. Arguably, the definition of type sections for anthropogenic deposits may be simpler in the distant future when they are preserved as rocks in the geological record and exposures are available for study.

Applicability of a hierarchical framework and naming of anthropogenic deposits

A hierarchical lithostratigraphical scheme allows the analysis of deposits of comparable characteristics at various scales, from the single trial pit to the entire nation. Without a hierarchy, a plethora of named units would be recognized, with no opportunity to show how these units relate to their neighbours. Hence, lithostratigraphy is more than a classification; it also conveys the geometry of the depositional basins and the processes forming the deposits.

International guidance recommends that each lithostratigraphical unit should be named after an appropriate geographical feature combined with the appropriate unit term (e.g. group, formation)

(Salvador 1994). Inclusion of a lithological term is discouraged by Salvador (1994). However, genetic and lithological descriptors have been used extensively within the classification scheme for natural Quaternary deposits (McMillan *et al.* 2011). Chronostratigraphical or biostratigraphical designations are kept separate as parallel schemes. The use of the same geographical term for units of different status (e.g. formation and member) is not recommended.

Formations. The formation is the primary formal mappable unit of lithostratigraphy (Salvador 1994; Rawson *et al.* 2002; North American Commission on Stratigraphic Nomenclature 2005). A formation is generally defined as the smallest mappable unit that has lithological characteristics which distinguish it from adjacent formations (Rawson *et al.* 2002). However, 'mappability' is a poorly defined criterion, for it depends on the scale of mapping and, in 3D models, scale variations may allow both members and beds to be shown as mappable units. Formations should be regionally significant mappable units, and in Great Britain they are readily represented on 1:50 000 scale maps (McMillan *et al.* 2011).

For natural deposits, formations typically range in thickness from a few metres to several hundred metres, although the definition of formations is scale-independent. In bedrock and superficial deposits, the formation commonly extends over a regional scale, commonly across part or all of a depositional basin or catchment area. For example, a glacial till of Devensian age has different characteristics to a till of Anglian age, and both are classed as formations across the area of former influence of a particular ice sheet. It is important to recognize, in this example, that age is not used as the criteria for recognizing two distinct units, but that the environmental circumstances related to ice sheets of different ages are sufficiently distinctive to allow lithological differences to be recognized between the two formations and their relative stratigraphical position to be determined. Likewise, it can be argued that in Great Britain the broad lithological characteristics of medieval anthropogenic deposits associated with small-scale urban developments are markedly different from Victorian era deposits associated with industrialization and large conurbation development. These are different again from the post-industrialization consumer-driven diversity and bulk of waste products of the present, which may again be different to deposits in a future mineral resource-depleted world. Broad lithological differences with time are described above and are shown in Figure 11.

In Figure 14, an attempt is made to recognize three distinct anthropogenic formations in the Swansea area. The oldest anthropogenic deposits typical of the pre-Industrial Revolution era are of limited lateral extent and are largely associated with building of robust defensive structures, with any habitations of this age not associated with mappable extents of anthropogenic deposits. During the Industrial Revolution, Swansea was a major centre for metal smelting and coal mining, and the extensive anthropogenic deposits are typically related to spoil from extractive or processing industries. After World War II, with the decline of heavy industry in the region, many of the deposits are engineered ground for new houses and roads, and the provision of raised ground to facilitate developments on floodplain areas (Waters *et al.* 2005). These three time periods are responsible for radically different deposits that may be considered to represent single formations. However, where reworking of these deposits has occurred, it may not be possible to recognize to which of these formations a particular deposit belongs. This may be the case in the example provided in Figure 14, where Industrial Revolution era foundry deposits have been reworked and redeposited to form raised fill. If information of the land-use history was not available, it would not be possible to identify within which formation the reworked deposit should be included. The hierarchical nature of lithostratigraphy always allows the unit to be defined as the more inclusive unit, in this case as an undifferentiated part of a group.

It may not be necessary or desirable to force all anthropogenic deposits into a formal lithostratigraphical scheme at formation level. For example, an isolated deposit of uncertain age or origin may not fit easily within such a scheme. Lithogenetic units are locally mappable assemblages of strata, considered without regard to time (Schenck & Muller 1941; Salvador 1994). A lithogenetic unit, mappable or otherwise, is defined by its lithology, morphology and inferred mode of origin (genesis). For Great Britain, BGS classifies lithogenetic units according to the BGS Rock Classification Scheme (RCS) for natural superficial deposits (McMillan & Powell 1999). For anthropogenic deposits, the morphogenetic classification scheme of Ford *et al.* (2010*a*) is a practical mapping and descriptive tool.

Groups and subgroups. Grouping of formations is desirable, although not required, particularly to aid regional mapping (Salvador 1994). Groups and subgroups may or may not be composed entirely of named formations (North American Commission on Stratigraphic Nomenclature 2005), but the establishment of groups without constituent formations should be avoided (Salvador 1994). Groups can be established for formations that reflect the diverse

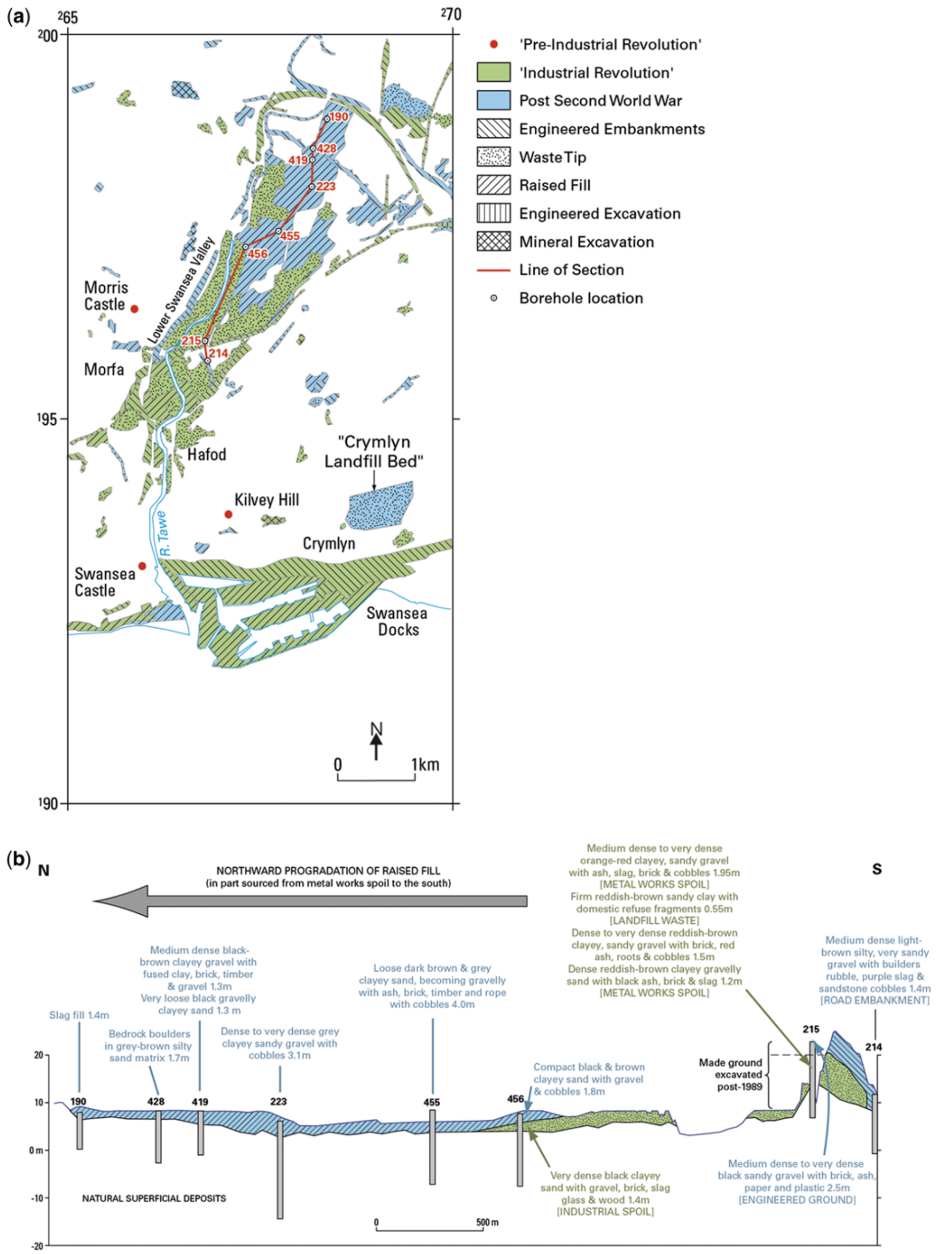

Fig. 14. Example from the Swansea area showing classification of deposits using the existing Ford *et al.* (2010*a*) morphogenetic scheme (ornament) and how they could be reclassified using a lithostratigraphic scheme (colour). The section shows the description of artificial deposits, as recorded in selected boreholes. This demonstrates a problem with lithostratigraphical classification in that the deposits are still mobile, with excavation of metal works spoil deposited originally prior to 1945, to be redeposited in recent years as raised fill in the north of the section. Without an understanding of the history of development of the area it may be difficult to know within which formation the deposits described as ‘slag fill’ should reside. It also shows that such artificial deposits have an inherent diachroneity in their deposition.

lithologies associated with the principal inferred modes of origin.

Groups permit the mapped formations to be integrated with deposits showing similar lithological or genetic characteristics to allow assessment of successions at broader scales within that basin or catchment area. In the context of natural superficial deposits, it can allow, for example, all glacial deposits to be included in a single group within the area of that ice sheet. This starts to express information on the extent of influence of that ice sheet. In the context of this study, it may be helpful to be able to link all artificial deposits within a given domain of comparable evolution of human activities into a single group. In the example given above of Swansea (Fig. 14), it resides within a broad area of the South Wales Coalfield in which conurbations went through a common history of heavy industries associated with rich mineral resources, followed by decline during the mid-twentieth century and subsequent rejuvenation during recent years. It would be possible to recognize all deposits within the influence of the South Wales Coalfield as part of a single group (Fig. 3), in the same way that domains were erected for superficial deposits to identify catchment groups (McMillan *et al.* 2005). However, in this case the domain is identified by the complex social and economic development of an area, in part controlled by the underlying geology, development of transport networks or simply historical accident. This is a subjective approach, and it is recognized that areas at the margins of a domain may be difficult to define. By recognizing a series of domains that reflect distinct groups, it is envisaged that where anthropogenic deposits are less common in rural areas between the domains, they would be included within formations, but they need not belong to groups.

Supergroups. The most inclusive unit, the Supergroup, as applied to bedrock and superficial deposits is typically used to denote deposits of similar bulk characteristics present at a national scale. In this context, when looking at geological maps and models, it would be helpful to be able to distinguish all anthropogenic deposits, recognized as a single named unit, from natural deposits. For Great Britain, it is suggested that a British Anthropogenic Deposits Supergroup would distinguish the artificial deposits from natural Quaternary superficial deposits of the Great Britain Superficial Deposits Supergroup of McMillan *et al.* (2005) and from bedrock lithostratigraphical designations (Table 2).

Members and beds. More exclusive units, members and beds, may be usefully defined for local to site-specific studies. The lower level units with member and bed status are typically units that may be defined at only a few well-exposed sections or from single boreholes. Such units may not be amenable to systematic and widespread mapping away from their stratotypes.

A member is the formal lithostratigraphical unit next in rank below a formation, and is always part of a formation (Salvador 1994). A member may extend from one formation to another (Salvador 1994). A formation need not be partially or totally subdivided into members. Members are commonly used to define a lithological sequence within a succession of distinctively different lithologies that are representative of the parental formation. For example, a shale member may be recognized within an interval of limestones that dominate a formation. For anthropogenic deposits, a member may be usefully defined to identify deposits of broadly similar genetic origin within a formation. For example, given an identification of a post-World War II succession in the Swansea area as a formation, it would be possible to recognize a member that included areas of engineered land-raising fill above the floodplain, and road and motorway embankments (Fig. 14). These may have similar lithological characteristics that are quite distinct from, say, landfill deposits. In the example provided, such deposits are sufficiently extensive to warrant identification as a member. This would equate with the Raised Fill and Engineered Embankment Type of the BGS enhanced classification scheme (Ford *et al.* 2010*a*), and it is accepted that there would be considerable overlap of the schemes.

A bed is the smallest formal unit in the hierarchy of sedimentary lithostratigraphical units (Salvador 1994). This should not be confused with a sedimentological bed, which identifies sediments deposited during a single event. A lithostratigraphical bed can comprise one or more sedimentological beds. Bed names are commonly applied to distinctive units that may be thin, or known only from a borehole or single exposure. Beds may be selected to provide useful marker units representing single events with one lithology, although, commonly, beds are left as informal and may lack definition of type sections. A bed could represent an extensive fossiliferous marine band in bedrock strata, or a locally developed peat in a superficial deposit. For artificial deposits, a bed could represent a single volume of deposit with a distinct lithological characteristic; for example, the Crymlyn Landfill Bed (Fig. 14). This would equate with the Landfill Waste Tip Unit (Domestic Refuse) of the BGS enhanced classification scheme (Ford *et al.* 2010*a*). Significant units could be delineated based upon morphogenetic and/or lithological characteristics, and named after a prominent location associated with the deposit, but may be left informal. It is not envisaged that all isolated masses of artificial

Table 2. *Examples of lithostratigraphical hierarchies for bedrock and natural superficial deposits (following McMillan et al. 2005) and possible application to anthropogenic deposits (Ford et al. 2008; Waters et al. 2009)*

Lithostratigraphical level	Example sedimentary sequence (extent) [maximum thickness]	Example superficial deposit (extent) [maximum thickness]	Example Artificial ground (extent) [maximum thickness]
Supergroup	Coal Measures Supergroup (Great Britain) [1900 m]	Great Britain Superficial Deposits Supergroup (Great Britain) [200 m]	British Anthropogenic Deposits Supergroup (Great Britain) [65 m]
Group	Pennine Coal Measures Group (central and northern England and North Wales) [1900 m]	Britannia Catchments Group (Great Britain) [100 m]	South Wales Industrial Group (South Wales Coalfield) [12 m]
Formation	Pennine Upper Coal Measures Formation (central and northern England and North Wales) [800 m]	Breighton Sand Formation (Vale of York) [>6 m]	Swansea Industrial Revolution Formation (Lower Swansea Valley) [9 m]
Member	Hemsworth Member (Yorkshire coalfield) [93 m]	Skipwith Sand Member (Vale of York) [2.4 m]	Lower Swansea Valley Foundry Waste Member (Lower Swansea Valley) [9 m]
Bed	Upton Coal (Wakefield) [1.8 m]	Skipwith Peat Bed (Vale of York) [0.2 m]	Hafod Foundry Waste Bed (Crymlyn) [9 m]
Local unit name	Third Cherry Tree Marker (Wakefield) [14.78 m]		Applicable, to local description, but far too many names to formally adopt

deposit should be named as lithostratigraphical beds, in the same way that not all sandstones in a cyclic sedimentary unit are named beds.

A significant problem with the approach expressed above is the inherent separation of deposits with the same name. In bedrock and superficial deposits, subsequent erosion can result in isolation of parts of a named unit, but the assumption is that at the time of deposition they were laterally contiguous. This is clearly not the case in the scheme proposed above, which could result in a series of isolated colliery spoil tips being included within a single member. Either, it is necessary to argue that lithostratigraphy needs to evolve as a classification scheme to consider the unique circumstances of artificial deposits, not currently considered in any scheme, or it be argued that lithostratigraphical definitions are fixed and cannot be modified to incorporate the vagaries of man-made stratigraphy. This is a decision that would need to be made by the International Commission on Stratigraphy.

Indirect evidence

The practical application of lithostratigraphy in geological mapping where exposure is limited by weathering, soil cover, vegetation or buildings involves a range of indirect evidence to support the extrapolation of boundaries between outcrops or lithological boreholes. Lithostratigraphy permits indirect evidence for the identification of units and their boundaries where lithological identity is difficult to determine (Salvador 1994). Compared with natural deposits, anthropogenic deposits typically exhibit fewer exposures because of their function, managed nature and age (i.e. in most cases, natural erosion has not created exposures of artificial deposits). Indirect evidence is, therefore, a key factor when considering a lithostratigraphical approach to the classification and mapping of anthropogenic deposits. Common sources of indirect evidence are described below.

The indirect evidence used most commonly in lithostratigraphical mapping in Great Britain is geomorphology. Many natural deposits are associated with characteristic landforms. These may form as a result of particular physical responses to weathering (e.g. the creation of escarpments or ridges) or they may be constructional, reflecting the original form of the deposit (e.g. a moraine or alluvial terrace). Characteristic slope profiles are sometimes diagnostic of particular bedrock units and useful for geological mapping (Aldiss *et al.* 2012). Constructional landforms are typically used in the characterization and mapping of relatively fresh superficial deposits, and are exhibited by many surficial anthropogenic deposits (McMillan *et al.* 2005).

Landform information for anthropogenic deposits may be obtained by direct or remote observation, including the use of topographical data, aerial photography and digital elevation models (DEMs). In recent years, the increased availability and quality of DEMs, along with the development of visualization systems, has transformed the geomorphological mapping and the study of artificial ground, especially in urban conurbations where high-resolution data are now readily available. DEMs complement topographical data, allowing distinct bodies of anthropogenic deposit to be delineated, and indicative thicknesses and volumes to be assessed (Fig. 15). Where successive DEMs are available, the sequence of deposition and temporal change in volume of artificial deposits may be calculated. Multiple ages of aerial photography or topographical maps can prove equally valuable in assessing geomorphology and human landscape evolution, including evidence of the depositional process that may inform the lithostratigraphical classification of anthropogenic deposits (Fig. 12).

The association between geological deposits and distinct biotas is a form of indirect evidence used to map natural deposits. The physical and chemical properties of deposits and their soils can influence the vegetation that they support, either in terms of species affinity or growth characteristics. Arguably, these responses are more apparent in the case of anthropogenic deposits that typically exhibit properties considerably different to those of natural deposits. The age of anthropogenic deposits may also define vegetation characteristics (Schadek *et al.* 2009). Indirect evidence from vegetation may be of particular value in mapping disused anthropogenic deposits and those with degraded morphologies. Although anthropogenic deposits are known to provide unique habitats for particular species (e.g. metal-loving plants), the practical use of vegetation response in geological mapping relies on non-specialist, directly observable characteristics such as crop type. Indirectly, vegetation response to anthropogenic deposits is also used in the interpretation of aerial photography and remote sensing for the purpose of land-use classification (Slonecker *et al.* 2010).

In many situations, the geophysical properties of anthropogenic sediments are significantly different to those of natural host lithologies. A range of techniques including resistivity imaging, ground penetrating radar (GPR) and gravity surveys are used in archaeological, engineering and environmental studies to delimit and characterize anthropogenic deposits (Fenning & Williams 1997; Guerin *et al.* 2004; Kulessa *et al.* 2006; Boyce *et al.* 2009; Boudreault *et al.* 2010). GPR, in particular,

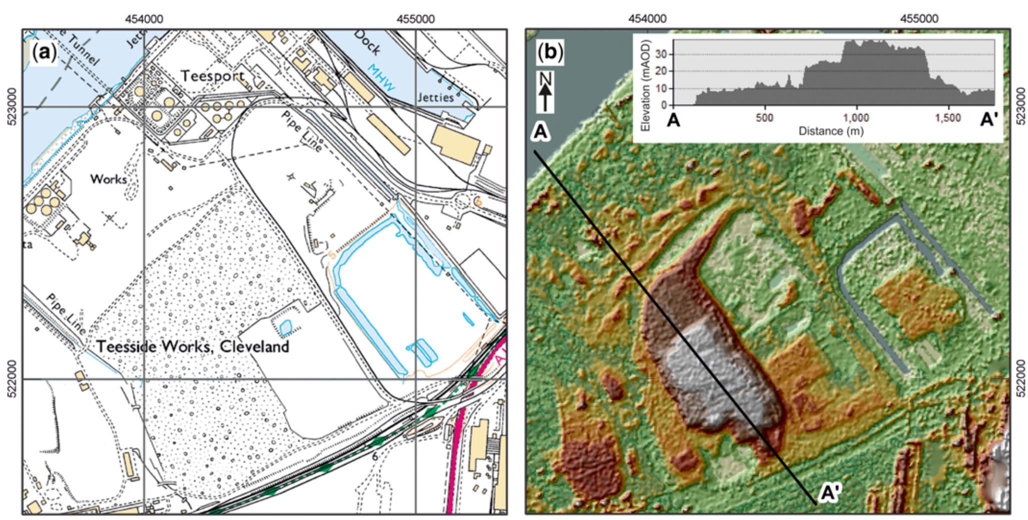

Fig. 15. (**a**) Topographical map and (**b**) DEM data for an area of NE England where the iron and steel industry has resulted in extensive anthropogenic modification of the landscape, including the creation of large waste tips. The DEM data resolve the geomorphology of the anthropogenic deposits in considerable detail, picking out distinct regions within the area shown on the topographical data as a single body of waste (stippled area). The anthropogenic deposits in this area reach around 40 m in elevation (see the inset elevation profile), some 30 m above the surrounding land surface. Topographical data ©Crown Copyright Ordnance Survey. All rights reserved. NEXTMap Britain elevation data from Intermap Technologies.

is used extensively by archaeologists to characterize anthropogenic deposits on a site scale (Bladon *et al.* 2011). Although limited coverage of suitable geophysical data prevents their widespread use in the systematic characterization of anthropogenic deposits, they may be of considerable value in resolving concealed deposits and the effects of anthroturbation including abandoned mine workings (Chambers *et al.* 2007).

Summary

The magnitude of direct anthropogenic transformation of the landscape and the shallow subsurface is globally significant. Human activity associated with urbanization and the exploitation of natural resources is now responsible for a greater flow of materials than natural sedimentary systems. Materials directly and deliberately moved by humans in the novel sedimentary environment are defined as anthropogenic sediments, and their classification is the focus of this paper. Anthropogenic sediments and their deposits are significant in terms of their engineering and environmental properties. They are potential material resources and sources of evidence in archaeological studies and the ongoing debate over the Anthropocene.

Classification schemes created for a diversity of disciplines can be used to varying degrees in the geological study of anthropogenic deposits. Existing classification schemes used by geoscientists in Great Britain for anthropogenic deposits are largely based on morphogenetic attributes. Whilst these approaches offer practical means of depicting the gross distribution of anthropogenic deposits for the purpose of geological mapping and modelling, they do not allow different phases or lithologically distinct deposits to be differentiated. In the case of natural superficial and bedrock sedimentary deposits, a lithostratigraphical approach is used. Lithostratigraphy is based on observable lithological characteristics and the spatial relationship of deposits. This approach distinguishes different phases of deposition, allowing units to be correlated. In the case of anthropogenic deposits, lithostratigraphy could allow the human transformation of the landscape to be charted.

A lithostratigraphical approach to anthropogenic deposits has not previously been attempted. Although natural and anthropogenic sediments share many similarities, they differ in several key respects. Anthropogenic sediments are typically thinner, discontinuous, poorly exposed, lithologically heterogeneous, rich in novel materials and, in many cases, their upper surface is represented by the present-day land surface. Natural superficial deposits can exhibit many similar characteristics to anthropogenic deposits and the challenges these pose to lithostratigraphical classification have been recognized by previous studies. This paper considers whether current lithostratigraphical procedures could be applied to anthropogenic deposits to establish a meaningful and useful classification. A summary of the main findings, with reference to the principles of lithostratigraphy, is presented in Table 3.

Lithostratigraphy is used to classify sediments or volcanic deposits that conform to the Law of Superposition. Many anthropogenic sediments satisfy this requirement; they are typically deposited subaerially, resting on older anthropogenic deposits or, more commonly, sitting unconformably on natural superficial or bedrock deposits. The unconformable boundary between natural and anthropogenic deposits may be relatively easily identified. However, the identification and correlation of significant discontinuities within successions of anthropogenic sediments may be more problematic. Where anthropogenic materials are enclosed by earlier natural or anthropogenic deposits (e.g. in the case of back-filled mine workings), they may be considered as anthropogenic intrusives and classified as lithodemic units. The extensive and increasing interaction between humans and the shallow subsurface may be considered a form of bioturbation or anthroturbation. The preservation potential of anthroturbation in the rock record is considerable and may be a significant factor in recognizing the Anthropocene.

Many anthropogenic units, being surficial deposits, have no overlying strata. Their upper bounding surface is defined as the present-day land surface that may be subject to a combination of natural erosive or depositional processes, or, in the case of many urban areas, frequent anthropogenically driven change. Where the original landforms are preserved, morphology may be used to classify the gross distribution of anthropogenic deposits. However, where landforms are destroyed or indiscernible (e.g. in the case of concealed deposits), a lithostratigraphical approach provides a means by which anthropogenic deposits may be classified and correlated.

Original lateral continuity is a defining characteristic of lithostratigraphical units. However, the lateral continuity and thickness of the majority of anthropogenic deposits is significantly less than that that of natural superficial and bedrock deposits. Social and economic factors dominate physical constraints in controlling the distribution of anthropogenic deposits. As such, individual deposits are usually discrete entities, bounded by limits other than physical constraints. Although geological maps based on existing morphogenetic schemes depict some extensive bodies of made ground, these

Table 3. *Summary of lithostratigraphical criteria applied to anthropogenic deposits*

Lithostratigraphical criteria	Satisfied by Anthropogenic deposits?	Examples of effective situations	Examples of exceptions/challenges
Law of Superposition	Yes – mostly	Most terrestrial deposits, resulting from the sequential emplacement of made ground including heritage deposits	Deposits related to subsurface engineering and storage including back-filled cavities and injected material (i.e. anthropogenic 'intrusives' or 'anthroturbation'); lithodemic classification may be appropriate
Original lateral continuity	Rarely – although 'yes' if broad scales considered	Deposits related to large-scale urban or industrial expansion (e.g. deposits associated with coalfield development); deposits associated with major socioeconomic or environmental drivers including conflict and climate change adaptation (e.g. flood defences)	Most deposits related to site-scale processes; deposits that result from the infilling of surface excavations. NB: in all cases, lateral continuity is a function of the scale of the study and the lithostratigraphical resolution used
Lithological distinction	Yes	Deposits imported from diverse supply areas; deposits incorporating characteristic (ideally time-varying) novel materials; deposits composed of contrasting proportions of natural sediment, novel materials and reworked natural deposits	Multiple deposits composed of locally derived natural material; deposits sourced from lithologically similar supply areas; deposits composed of reworked anthropogenic deposits
Definable type section/area	Rarely	Spatially extensive surficial deposits encountered in subsequent ground investigation boreholes; deposits classified as heritage deposits for which exposures are preserved. NB: type section definition of anthropogenic deposits may be simpler in the geological future	Poor natural exposure of deposits; restricted spatial extent may limit access to type sections/areas; extensive reworking and remodelling of deposits may prevent long-term preservation of type sections/areas
Hierarchical framework and naming	Yes – if broad scales considered	Deposits exhibiting broad lithological and stratigraphical characteristics that are indicative of particular novel environments, and may be grouped accordingly (see Table 2 for examples)	Anthropogenic units require broader ranges of thickness and lithological variability than natural units of equivalent status; anthropogenic deposits do not satisfy stipulation for original lateral continuity

typically represent amalgamations of multiple phases and types of deposit. Where instances exist of extensive anthropogenic sediments resulting from a single phase of deposition, they are typically associated with large-scale mining, industry and infrastructure. Arguably, such deposits also represent amalgamations and may be locally diachronous. However, in the context of a hierarchical lithostratigraphical framework they could be defined as a single unit at an appropriate scale. Anthropogenic deposits associated with a single phase of deposition are considerably thinner than equivalent natural deposits. Establishing lithostratigraphical units for anthropogenic deposits at a mappable scale will, in most cases, require the aggregation of deposits. Key historical events have resulted in significant temporal changes in the volume and extent of anthropogenic material deposited. These changes represent distinguishing characteristics that may support the application of lithostratigraphy to anthropogenic deposits. On a global scale, these changes are highly diachronous.

Lithostratigraphical units defined at the mappable scale should have distinguishing lithological characteristics. The lithology of anthropogenic sediments can be described using conventional descriptive approaches. The bulk composition of anthropogenic deposits is considered in terms of three components: natural materials disturbed by direct human action; natural sediments; and novel materials. Deposits dominated by disturbed and novel material are defined as anthropogenic. The composition and proportion of these components can vary between adjacent deposits, enabling their differentiation. These changes reflect different sediment supply areas, contrasting depositional processes or the relative age of deposits. Where material is locally derived or reworked, lithological distinction is problematic, and a lithostratigraphical approach may be unworkable. However, novel materials can aid the distinction between adjacent units and may provide markers for units of a particular age, akin to the use of fossil assemblages in natural deposits. The original bulk compositions of some types of anthropogenic deposits have varied considerably with time, these changes showing significant regional or global diachroneity. Significant changes often follow key historical events, and waste deposits, in particular, exhibit major temporal changes in their lithological character. As waste deposits are volumetrically the largest type of anthropogenic deposit, this presents a particular opportunity for lithostratigraphical classification in terms of providing distinctive lithologies. However, preservation potential of anthropogenic deposits must be considered when assessing their lithological characteristics as the composition of many deposits, including waste, is subject to significant change. Chemical and physical alteration can be considered analogous to diagenesis in the natural rock cycle.

The definition of a lithostratigraphical unit requires the designation of a type section or area. In the case of anthropogenic deposits, naturally occurring exposures are uncommon, ephemeral, and rarely provide an inclusive depiction of the deposit and its boundaries. Artificial exposures such as trial pits or excavations created during site redevelopment are similarly short lived. The lack of suitable exposures is a significant impediment to the application of conventional lithostratigraphical procedures to anthropogenic deposits. Borehole intersections offer potential type sections for anthropogenic deposits. However, borehole intersections through anthropogenic deposits commonly recover loose samples with disrupted boundaries, few suitable intersections are preserved for future reference and many deposits have little or no borehole coverage.

The hierarchical nature of lithostratigraphy provides a practical means of classifying and rationalizing deposits across a range of scales, with formations defined as the primary mappable unit. In the case of anthropogenic deposits, their thin, discontinuous and diverse nature renders impracticable and undesirable the definition of each individual body or landform as a separate formation. A possible approach to the lithostratigraphical classification of anthropogenic deposits involves the definition of units on the basis of broad lithological and stratigraphical characteristics that are indicative of particular novel environments. These novel environments and deposits may reflect dominant industrial or economic activity, or characteristic associations of activities, and be subject to changes with time. It is the particular lithostratigraphical characteristics of deposits of a particular time, rather than their age as such, that result in a distinctive stratigraphy that may be identified by a range of direct and indirect evidence, and grouped or subdivided accordingly. This approach is similar to that used in the lithostratigraphical classification of natural deposits. However, the range of thicknesses and lithological heterogeneity accommodated by an anthropogenic unit may be considerably greater than that of a natural deposit of a similar lithostratigraphical status, reflecting the inherent variability of anthropogenic deposits. Importantly, this approach allows the inclusion of deposits that were originally spatially isolated within a single unit (e.g. discrete mine waste tips or similar character combined into a single member). Current lithostratigraphical procedures require original lateral continuity and this would have to change if this suggested approach were accepted. Existing classification schemes for anthropogenic deposits may be used in parallel to lithostratigraphy to convey additional information on genesis and landform. In particular, the morphostratigraphical approach of Ford *et al.* (2010*a*) remains a practical mapping and descriptive tool.

Indirect evidence can be used in the identification of lithostratigraphical units and their boundaries. Sources of indirect evidence used routinely in the context of natural deposits are effective in the case of anthropogenic deposits. Aerial photography interpretation and geomorphological mapping, including the appraisal of DEMs, are well suited to delineating anthropogenic deposits with relatively fresh morphologies. Successive generations of imagery or data can be used to chart changing land use and indicate the potential location of concealed deposits. Geophysical surveys, although typically commissioned for purposes other than the study of anthropogenic deposits, can be used to reveal their subsurface geometry. However, the limited coverage of geophysical datasets precludes their widespread use for systematic mapping or modelling.

Conclusion

This study does not set out to define a lithostratigraphy for anthropogenic deposits. Its aim is to assess the applicability of current lithostratigraphical procedures to the classification of anthropogenic deposits. Lithostratigraphy was pioneered in the study of bedrock geology, and has been subsequently adapted for natural superficial deposits. Situations have been identified where anthropogenic deposits are shown to conform to many of the criteria for lithostratigraphy. The scale at which lithostratigraphy may be effectively applied to anthropogenic deposits may be significantly different when compared to natural deposits. However, even if lithostratigraphical units defined for anthropogenic deposits are relatively coarse, this approach affords the end user a level of functionality that is not supported by existing classifications of anthropogenic deposits.

It is clear that much remains to be done to determine the feasibility of any proposal to adopt a lithostratigraphical scheme for anthropogenic deposits. A truly global perspective is essential to ensure that the challenges identified here including scale, diachroneity, and other key differences between natural and anthropogenic deposits are appreciated and resolved. Should a lithostratigraphical approach to the classification of anthropogenic deposits be adopted, the revision of established stratigraphical guidelines would need to be considered. The incorporation of stratigraphical procedures for anthropogenic deposits alongside those for natural deposits in international guidelines would make a significant contribution to the study of anthropogenic deposits and the impact of human processes on the landscape. A consistent lithostratigraphical framework for anthropogenic deposits would, in turn, contribute to the definition and characterization of the Anthropocene.

However, significant changes to existing lithostratigraphical procedures would be required to provide an effective classification of anthropogenic deposits. These changes, and their potential impact across the stratigraphical column, would require careful consideration before being enacted. A practical solution would be to establish a complementary classification scheme designed specifically for anthropogenic deposits. Based on lithostratigraphy and incorporating elements of the current morphogenetic classification, this 'anthrostratigraphical' approach would combine relevant strengths from the existing schemes and could be tailored to accommodate the unique characteristics of anthropogenic deposits.

It is important to remember that chronostratigraphical schemes that define geological time intervals, such as the proposed Anthropocene Epoch, evolve in parallel with lithostratigraphical schemes that aim to characterize the physical attributes of rock masses. The inherently diachronous nature of lithostratigraphy, expressed in the novel sedimentary environment by the growth with time of urban conurbations or the gradual spread of novel processes and lithologies as a product of technical innovations, makes lithostratigraphy a poor criterion for defining the Anthropocene as such.

However, changes in lithostratigraphically discernible characteristics of anthropogenic deposits including rate of accumulation and lithological composition provide some support for the recognition of a significant signature immediately following World War II. Although earlier events and periods in history, including the Industrial Revolution, are associated with national and regionally significant signatures, the period following 1945, or the 'Great Acceleration of the Anthropocene' (Steffen *et al.* 2007), is marked by the first globally expansive change in the lithostratigraphy of anthropogenic deposits.

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