The forensic utility of reworked geological materials in soil

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ABSTRACT

Geological materials such as rock fragments, microfossils and mineral grains are continuously being entrained (i.e. reworked) into soil during natural weathering processes. Distinctive reworked rock types in soil, and specific components of them such as palynomorphs (organic microfossils), can prove extremely useful in forensic investigations, i.e. to connect (match) people to places. If the outcrop area of a unique rock is small and well mapped, it potentially has substantial evidentiary value in soil forensic studies. Furthermore, clay minerals, geochemical data and minerals may support the presence of a suspect at a crime scene. Modern pollen and spores extracted from soil samples in forensic investigations can be invaluable in linking suspects to crime scenes. This is because the majority of localities, especially those with natural vegetation, have characteristic (often unique) floral character. Reworked (i.e. largely pre-Quaternary) palynomorphs and other microscopic fossils may co-occur with the *in situ* (indigenous) pollen and spores. If these reworked forms have relatively short geological ranges, they can indicate the age of the bedrock, thereby further helping to place a person at a location. However, stratigraphically recycled palynomorphs in the soil can be somewhat rare and sporadic, and many rock units are entirely or virtually devoid of palynomorphs. Furthermore, glacial sediments such as till can provide highly mixed reworked palymomorph associations due to their typically heterogenous nature. These diverse assemblages are frequently highly distinctive hence can potentially provide very powerful forensic evidence. The potential of geological materials derived from bedrock in soil for forensic investigations is absolutely clear. Hence, the use of reworked microfossils, minerals and rock should be considered in any major crime where the evidence includes soil.

Keywords: forensic geology; minerals; palynomorphs; reworking; rock fragments; soil

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1. Introduction

The *in situ*, or indigenous, pollen and spores which have been incorporated into the pedosphere, and the type and composition of soil, can be successfully used to connect a person or persons with a specific locality. If soil, or any adherent pollen and spores, can be expeditiously collected from the belongings (e.g. clothing, footwear, tools, vehicle etc.) of a suspect, it is possible that analysis of that material can help to indicate that the owner was present at a crime scene (e.g. Popp, 1939; Horrocks et al., 1998; Mildenhall, 2006; Wiltshire, 2009, 2016; Warny, 2013; Babcock and Warny, 2014; Wiltshire and Hawksworth, 2014; Wiltshire et al., 2014, 2015; Williams et al., 2017; Laurence and Bryant, 2019; Warny et al., 2020).

In many forensic studies, *in situ* palynomorphs (e.g. pollen and spores) are analysed in parallel with the chemical/mineral composition of the soil and any characteristic items of refractory anthropogenic litter such as brick, glass, metal, paper, plastic, synthetic fibre etc. (Brown et al., 2002). The contemporary pollen/spore assemblages can characterise a specific location extremely effectively. There are many more plant pollen grain and spore taxa in comparison to the 12 or so principal silicate mineral species (Moore et al., 1991; Deer et. al., 2013; Klein and Dutrow, 2007). All plants have unique pollen grains or spores, and every geographical area (normally intra-biome) is characterised by different plant assemblages. Hence the huge variation in vegetation types, and taphonomic factors such as insects, water and wind, that modify terrestrial palynomorph assemblages, ensures that the nature of the diversity and the species spectra are highly distinctive, if not unique, of the majority of geographical localities. Most pollen and spores are transported various distances away from the donor (or source) plants by vectors such as insects and wind, rather than being preserved directly at or below their point of origin (Wiltshire, 2006). The relevant source areas of pollen and spores varies according to the specific nature of the landscape and the site (Hellman et al., 2009). For any site, the pollen and spores include a relatively small far-travelled component. Despite this, pollen/spore recruitment into soil is generally regarded as being highly localised, especially where the mode of pollen dispersal is entomophilous (Gavin and Brubaker, 1999). In summary, this means that the *in situ* pollen and spore assemblage can normally fingerprint a specific vicinity (Riding et al., 2007). Fungal spores are also extremely useful in forensic studies The taphonomy of fungal spores is highly complex. Despite this, most of these fall close to the parent fungal body and are thus highly characteristic of a small area (Wiltshire et al., 2014). Fungal spores have a long fossil record so may also be reworked into soil (Fig. 1).

Anthropogenic litter, chemical and mineral signatures in soil also vary considerably, and crime scene-suspect matches based on geochemistry, man-made input and mineralogy can have considerable value as evidence (e.g. Ruffell and McKinley, 2005; Pye and Croft, 2004; Pye, 2007; Donnelly et al., 2021). These studies normally corroborate other lines of evidence such as from DNA and/or pollen and spores.

Most forensic geological investigations are solely concerned with *in situ* materials. By contrast, this review, explores the potential of allochthonous microfossils (particularly palynomorphs), mineral grains and rock fragments reworked from the directly underlying bedrock into the soil in forensic investigations.

2. Soil and its geological dimension

Soil is a relatively thin layer of a mixture of gases, liquids, mineral grains, organic matter (humus) and organisms that partially covers the land surface of the planet (White 2006). It is termed the pedosphere, supports terrestrial plant growth and is a habitat to a diverse, rich soil biota. Soil is an integral part of the regolith (the layer of loose material overlying solid bedrock), and forms slowly from the gradual breakdown of bedrock by biological, chemical and physical weathering. Most soils exhibit a distinct profile with three main horizons, i.e. surface (A), subsoil (B) and substratum (C); these are overlain by plant litter and underlain by bedrock (Fig. 2, Weil and Brady, 2017).

The mineral fraction of soil is therefore largely derived from the directly underlying bedrock. Clearly, geology primarily influences the mineral content of the soil. However, it should be remembered that some mineral grains can be blown onto the soil, for example in dust storms derived from arid/desert regions. Therefore a sandstone will produce a dry, loose, sandy, well-drained soil, and a clay-rich rock such a mudstone, shale or siltstone will normally be overlain by a clayey, heavy, poorly-drained, wet soil. Soil minerals are normally medium and fine grained (i.e. the sand, silt and clay fractions). The weathering process does not always provide finely disseminated rock-derived material such as individual sand grains. Small rock fragments (i.e. granules and pebbles) may also be present, largely in the B and C horizons, especially if the overall soil profile is relatively thin (Fig. 2). If the topography is relatively steep, soil forms sporadically and the bedrock frequently outcrops directly (Fig. 3).

3. The utility of soil minerals and rock fragments in forensic investigations

Clearly the participants in, and victims of, many crimes may interact with soil. This means that if the footwear etc. of a suspect yields soil that includes distinctive fossils, rock fragments or mineral grains, this can help to place a person at a specific locality (section 1). The geology of much of the developed world, especially western Europe, is typically very well-known through systematic geological mapping by state and regional geological survey organisations. The concept of geological mapping was founded in the UK by the pioneering geologist William Smith (1769–1839), who produced the first nationwide geological map in 1815 (Sharpe, 2015). The British Geological Survey (BGS) was founded in 1835 and since then has produced detailed geological maps of the UK at different scales using analog and digital methodologies (Fig. 4; Wilson, 1985; Bain, 1986; Allen, 2003; Kessler et al. 2009).

If the outcrop area of a highly distinctive lithology (rock type) is small and well constrained, that rock type has substantial potential evidentiary value. Many igneous rocks have highly distinctive mineralogies and textures, and are unique to a specific locality. For example, the Shap Granite of Cumbria, northwest England is a well-known felsic igneous rock of Devonian age with characteristic potassium feldspar megacrysts which frequently exhibit Carlsbad twinning and a bimodal (coarse/fine) grain size (Fig. 5; Grantham, 1928; Cox et al., 1996). Shap Granite is present in a subcylindrical shaped pluton, and has a relatively small outcrop area of ~8 km^2 (Fig. 6; Stone et al., 2010, fig. 13). A soil sample from footwear or a vehicle which includes even part of one of these potassium feldspar megacrysts would be strong evidence of the presence of the wearer in the area ~3 km south of the village of Shap, near Penrith, Cumbria, northwest England. Another example of this is rhomb-porphyry, a porphyritic igneous rock with common diamond/lens (i.e. rhomb) shaped phenocrysts of anorthoclase feldspar in a fine-grained matrix, typically from the southeast of Oslo in southern Norway (Neumann et al., 1992). One possible constraint of using Shap Granite or rhomb-porphyry in a forensic case in an urban area is that both these rocks are extensively used as ornamental stone, hence have been widely transported away from their source areas.

Many other igneous rocks exhibit distinctive mineralogical and textural characteristics, and metamorphic and sedimentary rocks may also be highly indicative of a specific geographical area or rock unit. For example an aeolian (desert) sandstone such as the Dawlish Sandstone Formation of the New Red Sandstone Supergroup (Permian) will be largely composed of frosted quartz grains. This distinctive texture is produced by frequent grain collisions in windy conditions such as sandstorms, as opposed to quartz grains with a glassy surface texture in sandstone which accumulated in aqueous settings such as the Millstone Grit Group of Carboniferous age (Table 1; Tucker, 2001). Similarly, most sandstones include minor amounts of distinctive heavy (refractory) minerals such as rutile, tourmaline and zircon (Morton, 1985; Morton and Hallsworth, 1994). These relatively rare mineral species would potentially be useful in a forensic investigation. A region such as the Northwest Highlands of Scotland is largely underlain by metamorphic rocks, principally the schists of the Dalradian Supergroup of mid Neoproterozoic to Early Palaeozoic age (Stephenson et al., 2013). Porphyroblastic minerals such as garnet are resistant to weathering and are readily incorporated into the soil.

Many rock units such as the Carboniferous Limestone Supergroup (Tournasian–Visean), the Millstone Grit Group (Serpukhovian–Bashkirian), the New Red Sandstone Supergroup (Permian–Triassic) and the Chalk Group (Upper Cretaceous) have large outcrop areas in the UK (Fig. 4). Hence, soil rock fragment analysis on a crime scene based on these units would be considerably less geographically conclusive than a highly restricted lithotype such as Shap Granite. Nonetheless, a consistency of rock fragments on footwear etc., and the bedrock outcropping at a crime scene would nonetheless represent important supplementary evidence. A listing of the reworking potential of rocks by geological age in the UK, and hence their potential utility in forensic science is given in Table 1.

Hard, splintery rock types such as granite or limestone are optimal for forensic investigations because they generally weather relatively slowly. By contrast, clay-rich siliciclastic sedimentary rocks, such as mudstone, shale and siltstone, tend to weather to soft clay and silt rapidly and thus their residence time in a coherent state in the soil is relatively short (but well within the timescale of a forensic case). However, if a mudstone has a highly distinctive clay mineral signature, the soil overlying outcrops of this rock will reflect the characteristic clay mineral assemblage (Brindley, 1952; Moore and Reynolds, 1997; Munier et al., 2021).

This discussion has thus far focussed on physical macroscopic and microscopic rock fragments and mineral grains. By contrast, geological specimens can be subjected to geochemical analysis in automated high-resolution core scanners (Croudace et al., 2006). This can give highly accurate elemental abundance data using X-ray fluorescence (e.g. Ruhl et al., 2016). It is eminently possible that the elemental chemistry of the soil overlying a specific bedrock will be similar to the equivalent data from the specific stratum itself.

Therefore, X-ray fluorescence information based on comparative soil samples is potentially very useful in forensic studies.

4. Reworked fossils, with emphasis on palynomorphs, in forensic studies

4.1. Introduction

As with lithic (rock) fragments and mineral grains, fossils from sedimentary rocks can be reworked into soil profiles and these can be used in forensic studies. Macrofossils such as ammonites, bivalves, corals, echinoids and trilobites are highly unlikely to be used in this context because they are normally too large to, for example, become embedded in the treads of footwear or vehicle tyres. In stark contrast, the small size of microfossils, and their abundance and ubiquity in most sedimentary rocks, makes them ideal for forensic investigations (Brown, 2017).

Microfossils are animal or plant remains that have to be studied using a microscope (Armstrong and Brasier, 2005). They are biologically diverse and are made of calcite (e.g. calcareous nannofossils, foraminiferal shells and ostracods) complex organic biomolecules (palynomorphs), phosphate (conodonts) or silica (diatoms and radiolaria). Microfossils are normally highly abundant in the majority of sedimentary rocks, especially fine-grained siliciclastic lithotypes, and may occur in rock-forming proportions. An example of the latter is the Chalk Group (Upper Cretaceous) (Fig. 4, Table 1). This unit is a pure limestone which is virtually entirely formed of calcareous nannofossils, the remains of unicellular calcifying phytoplankton (Burnett, 1998; Mortimore et al., 2001; Hopson, 2005). Many microfossil species have restricted temporal ranges and because of this, together with their robust nature and ubiquity, are used in the oil and gas industry to constrain the biostratigraphical age of sedimentary successions penetrated by exploration and production wells (e.g. Stover et al., 1996; Wynn Jones, 2006).

Due to the stratigraphical restriction of many species, microfossils which are reworked into the soil profile can reliably indicate the age of the parent bedrock. Clearly this has major implications for forensic geoscience. If the soil from the property of a suspect contains *in situ* pollen and spores together with reworked microfossils characteristic of a crime scene, this is powerful evidence to place a person at the locality in question (section 1; Wiltshire, 1998). Certain reworked microfossils are superior to others for forensic work. Many soils are slightly acidic and this will tend to dissolve calcareous microfossils such as calcareous nannofossils, foraminiferal shells and ostracods. Furthermore, of the siliceous groups, diatoms are similarly susceptible to shell thinning and dissolution, and reducing levels of silicification (Lewin, 1961; Ehrlich et al., 2010; Petrou et al., 2019). Despite this, calcareous nannofossils, foraminifera and diatoms have all been used in in forensic studies (e.g. Bailey et al., 2017; Levkov et al., 2017).

Of the other major microfossil groups, reworked conodonts and palynomorphs are the most chemically and physically robust, hence will normally remain in the soil for longer than other microfossils (Riding, 2021). Conodonts are the phosphatic hard part remains of a group of extinct agnathan chordates which resemble eels (Briggs et al., 1983; Donoghue et al., 2000). Palynomorphs are organic-walled microfossils such as acritarchs, angiosperm and gymnosperm pollen grains, chitinozoa, dinoflagellate cysts, fungal spores, microforaminiferal linings, plant spores, prasinophytes and scolecodonts (Jansonius and McGregor, 1996; Riding, 2021). Conodonts have a range of Cambrian to Triassic so are entirely absent from the Jurassic onwards. By contrast, palynomorphs are first found in Proterozoic rocks, and are extant. The stratigraphical extents and the taxonomic richness of the major ten palynomorph groups are illustrated in Fig. 1. Furthermore, they are substantially more abundant, biologically/taxonomically diverse, smaller and ubiquitous than conodonts. Thus, of all the groups of microfossils, allochthonous palynomorphs have by far the greatest utility in forensic geocience.

Many soil forensic samples are examined for *in situ* pollen and spores, and thus the same laboratory preparation will also contain any reworked palynomorph (Riding, 2021). Because of the clear advantages of palynomorphs over the other microfossil groups, the remainder of this account will concentrate on them. However, the principles discussed are applicable to all microfossils.

4.2. Reworked palynomorphs in general

Palynomorphs are common reworked components in sedimentary rocks. Their small size means that if small fragments of a pre-existing sedimentary rock are mobilised during weathering, these can be incorporated into a younger sedimentary unit. This scenario means that the reworked palynomorphs are protected from damage from oxidation as they are fully surrounded by rock matrix. Palynomorphs are extremely chemically robust, but they can be degraded and ultimately destroyed by oxidation during weathering and microbial activity (Riding, 2021). A familiar example of the reworking of pre-Quaternary palynomorphs is the stratigraphical recycling of Carboniferous spores into Mesozoic strata (e.g. Windle, 1979; Riding et al., 1999; Hesselbo et al., 2020). Similarly, Palaeozoic and Mesozoic palynomorphs may be reworked into Cenozoic strata (e.g. Collinson et al. 1985). Because they reliably reflect parent material, reworked palynomorphs have been frequently used to determine the provenance of sedimentary rock units (e.g. Streel and Bless, 1980; Eshet et al., 1988; Riding et al., 1997; Lopes et al., 2014). If a soil forms above a bedrock of Pleistocene (Quaternary) age, reworked pollen and spores may be recruited into the soil profile. These allochthonous palynomorphs will probably be indistinguishable from their modern counterparts because virtually all Quaternary plants are extant.

As an analogy for forensic studies, one of the most successful use of reworked palynomorphs is their use in determining the provenance of glacial sediments of all ages, and hence glaciers. The glacier picks up rock fragments as it slowly moves, and these are deposited as till when the glacier melts. If palynomorphs extracted from a till are from distinctive lithostratigraphical units, as determined from biostratigraphy, the flow path of the glacier can be reconstructed (e.g. Lee et al., 2002; Davies et al., 2009; Powell et al., 2016; Hall and Riding, 2016; Hall et al., 2016; Rose et al., 2021 for Quaternary glacigenic sediments). Similarly, Harding et al. (2004) used dinoflagellate cysts and other marine palynomorphs to help determine the provenance of flint artefacts from the UK.

4.3. Reworked palynomorphs in soil in forensic investigations and some constraints on their use

Reworked palynomorphs in soil will normally be rare in comparison to the *in situ* pollen and spores. It is possible that derived specimens may be relatively common, for example if a spore-rich coal or highly organic shale is incorporated into the soil profile. In the case of the latter, Lower and Upper Jurassic black, bituminous shales such as Mulgrave Shale Member (Lower Toarcian) and the Kimmeridge Clay Formation (Kimmeridgian) regularly provided stratigraphically recycled palynomorphs into tills in the UK (e.g. Busfield et al., 2015; Hodkin et al., 2016). This is due to the relative mechanical robustness and the resistance to oxidation during weathering of these relatively hard and physically strong lithotypes.

Certain palynomorph groups and ages may be more frequent than others. Some Early Palaeozoic acritarchs and most chitinozoa of this age can be relatively refractive and hence may readily survive in soil. Likewise, many Carboniferous spores are thick-walled and robust (Smith and Butterworth, 1967). Genera such as *Cingulizonates*, *Densosporites Radiizonates* and *Tripartities*, and species such as *Cirratriradites saturni* and *Lycospora pusilla* tend to rework easily and may even survive more than one sedimentary cycle (Riding et al., 2003).

Some Mesozoic and Cenozoic dinoflagellate cysts may be thin-walled and, it is the thicker-walled genera such as *Cribroperidinium* that tend to be most frequently stratigraphically recycled (Riding et al., 2003). A montage of palynomorphs which may be regularly reworked is given as Fig. 7. Table 1 lists the palynomorph groups characteristic of the Phanerozoic of the UK, period-by-period.

It should not be expected that reworked palynomorphs from bedrock will be present in every sample of soil. Organic microfossils are only sporadically recorded and this is due to several factors. These include the dominance of *in situ* pollen grains and plant spores over reworked palynomorphs, oxidation or partial oxidation of allochthonous pre-Quaternary palynomorphs in the soil profile, and palynomorph-free or organic–lean bedrock. The sporadic nature of reworked palynomorphs in soil may, however, be somewhat of a misconception. This is because most forensic palynologists are specialists in modern pollen and spores. If these practitioners encounter aquatic palynomorphs and/or Palaeozoic/Mesozoic pollen and spores, they may simply classify them as indeterminate forms or 'reworking'. For the latter reason, it is currently not possible to provide a reliable guide to the occurrence and relative proportions of reworked palynomorphs in soil.

As mentioned above, not all rock units yield palynomorphs. For example, all igneous and metamorphic ('crystalline') rocks are devoid of any fossils. Another factor is, if the uppermost part of the bedrock has been heavily weathered, the oxidation during this process will probably have destroyed much of the sedimentary organic mattter including the palynomorphs (Riding, 2021). Furthermore, many limestones and sandstones are extremely organic-lean and will not generally contribute many, if any, palynomorphs to the soil. Examples of organic-poor lithostratigraphical units are the Carboniferous Limestone Supergroup and the Millstone Grit Group of Carboniferous age in the UK (Table 1). As mentioned above, the most promising bedrock type for palynomorphs would be a dark, fine-grained clay rich sedimentary rock.

Much of the UK is blanketed by various glacial sediments of Quaternary age (e.g. Clark et al., 2004). These include glaciofluvial deposits, glaciolacustrine clays, outwash sands and gravels, and till. Of these, the glaciolacustrine clays and till are the most consistent in yielding palynomorphs. Both these sediments commonly yield palynofloras (Riding et al., 2003; Hodkin et al., 2016). In the case of till, the content of these assemblages is dependent on the sedimentary rocks entrained into the ice on route taken by the glacier. Frequently, tills contain a mixture of Palaeozoic, Mesozoic and Cenozoic palynomorphs (Busfield et al., 2015). For example the Irish Sea Till from offshore west Wales contains a particularly wide variety of organic microfossils (unpublished data). This admixture of palynomorphs can be potentially extremely helpful in forensic cases. If the mixture is highly characteristic of a specific glacial sediment the palynomorphs from, for example, a glaciolacustrine clay or till may have substantial evidentiary value. Taphonomic factors dictate the configuration of reworked palynomorphs in the matrix of a till. This means that the palynomorphs in a till are substantially variable, and hence could be used to link a suspect to a place via a comparison between a crime scene and an exhibit. On the other hand, if the abundance and variety of pre-Quaternary palynomorphs is too low, the association may not be conclusive of a particular locality.

5. *Modus operandus*

If there is soil evidence in a crime, especially where there is a specific locus such as a body deposition site, the geoscientific element should at the very least be considered in any forensic investigation. The bedrock geology should be identified using up-to-date geological maps, and consideration should be made if the relevant lithostratigraphical unit would potentially provide diagnostic lithic fragments, microfossils or mineral grains. A consultant, or consultants, could then be employed to check any soil samples for these materials. The same palynomorph slides as used by the expert in modern pollen and spores could be used by the pre-Quaternary palynology consultant. The same preparation procedures are used to extract and concentrate modern pollen and spores and their pre-Quaternary counterparts (Riding, 2021).

6. Conclusions

This article seeks to briefly review the use of geological materials which have been incorporated into the soil in forensic investigations. These are microfossils (with the emphasis on palynomorphs), lithic fragments and mineral grains that are entrained into soil during its formation. The main aim of this paper is to inform investigative authorities of the potential of reworked materials in the soil as evidence, principally to connect people to places. Because bedrock is continuously being weathered, microfossils and small rock fragments enter the pedosphere from below at a relatively constant rate. This means that potentially distinctive rock types, which may include characteristic palynomorphs and minerals, become reworked into the soil. If the geological material in soil on the clothing, vehicle etc. of a suspect matches that at the crime scene, this helps to link that person to that place. If the outcrop area of distinctive or unique rock type is relatively small and well known, it clearly has substantial potential evidentiary value. Similarly, the clay mineral assemblage, geochemical profile, mineral species and mineral surface texture may help to link a suspect to a locality. This is especially important in missing person and clandestine grave searches.

Reworked macrofossils have limited utility in forensic geoscience due to their relatively large size, however microfossils can potentially be extremely useful largely due to their abundance, small size and ubiquity. Of the several groups of microfossils, palynomorphs are most likely to be useful forensically. Any microfossil species with restricted temporal ranges which are reworked into the soil profile can accurately indicate the age of the bedrock. Therefore, this also can help place a person at a specific locality. It should be remembered that reworked palynomorphs in soil can be relatively rare and sporadic, many rock types and units do not yield palynomorphs, and glacial tills can provide a diverse, mixed (and hence potentially complex) palynomorph associations.

There are presently no published examples of reworked palynomorphs being used in a criminal case. In order to better demonstrate the utility of soil geological materials as lines of forensic evidence, it would be beneficial to undertake pilot studies in the future. These could be, for example, palynological analyses of soils developed over specific lithostratigraphical units or in different soil types. Additionally, it would be beneficial to execute detailed studies of the absolute palynomorph concentrations throughout specific soil profiles. This topic would also markedly benefit from specialists on modern pollen and spores starting to document reworking in a much more consistent and robust manner.

In summary therefore, the use of geological materials extracted from soil samples in a forensic investigation should be seriously considered in any major crime where soil forms part of the array of evidence.

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Display materials:

Fig. 1. The overall stratigraphical extents of the ten most important palynomorph groups adapted from Riding (2021). The relative widths of the lines indicate overall trends in taxonomic richness. Note that the diversity variations depicted here are strictly indicative in that the breadths of the lines are not precisely calibrated to numbers of taxa. The dashed lines indicate that the respective palynomorph group is relatively sparse. The ranges and

taxonomic richness trends are taken from key publications such as Millay and Taylor (1976), MacRae et al. (1996) and Grahn and Paris (2011).

Fig. 2. A typical soil profile illustrating the three main soil horizons overlain by an organic-rich layer of plant litter and underlain by solid bedrock. The A (surface) horizon comprises humus-rich topsoil and is underlain by clayey subsoil (the B horizon or subsoil). The C (substratum) horizon consists of weathered rock fragments. This diagram is adapted from several sources including Weil and Brady (2017).

Fig. 3. A small outcrop of bedrock in moderately steep grassy terrain within an upland setting; note the relatively thin soil surrounding the outcrop. The very thin soil at these type of localities will be very rich in fragments of the bedrock. This locality is ~0.75 km NNW of Wildboarclough, Cheshire, UK (NGR SJ 98017 69312) and the rocks exposed are dark shales of the Millstone Grit Group intercalated between a *Bilinguites superbilinguis* marine band and the Chatsworth Grit (Pennsylvanian).

Fig. 4. A small scale geological map of the UK and Ireland produced by the British Geological Survey (BGS) illustrating the principal rock types, and the ages of the metamorphic and sedimentary rocks. Individual lithostratigraphical units, such as the Millstone Grit Group mentioned in the text, are not distinguished at this scale. Substantially larger scale maps are available from BGS. Geological map BGS © UKRI (2019).

Fig. 5. A cut and polished hand specimen of Shap Granite from Shap Quarry, Cumbria, northwest England (NGR NY 55884 08519). The specimen is curated in the National Building Stone Collection of BGS. This image is BGS number P750651 and is used with permission. The size of the specimen is 150 mm x 115 mm. Note the highly distinctive texture of abundant potassium feldspar megacrysts in a much finer-grained groundmass. This bimodal crystal size in indicative of two distinct phases of cooling. The first of these stages was slow, in a deep crustal setting which allowed the potassium feldspar megacrysts to form. By contrast the second was substantially faster, clearly in a shallower position in the crust thereby causing the minerals in the groundmass to crystallise (BGS © UKRI).

Fig. 6. A geological map of the Lake District in northwest England to illustrate the relatively small areal extent (~8 km^2) of the Shap Granite outcrop. The Shap Granite Pluton (Sh) is located in the Shap Fells of Cumbria, adjacent to the northeast corner of the Windermere Supergroup and is part of the Northern England Devonian Plutonic Suite. This map is themed to illustrate the principal Ordovician and Devonian igneous bodies and their relationship to major structural features. This figure is from Stone et al. (2010, fig. 13) and BGS file P916043.jpg is reproduced with permission BGS © UKRI http://earthwise.bgs.ac.uk/index.php?title=File:P916043.jpg&filetimestamp=20160412171113&.

Fig. 7. A montage of nine selected aquatic and terrestrial palynomorphs from the Silurian, Carboniferous, Jurassic, Cretaceous and Paleogene.

1. The cryptogam spore *Reinschospora speciosa* (Loose 1934) Schopf, Wilson & Bentall 1944 from the Argill Shell Bed at Argill Beck, Stainmore, Cumbria, UK (Lower Pennsylvanian [Bashkirian]). BGS specimen number MPK 7433; 94 µm in diameter.

2. The cryptogam spore *Concavissimisporites* sp. from the Wealden Group (lowermost Cretaceous [Berriasian]) of southeast England. BGS specimen MPK 14717; 62 µm in diameter.
3. The gymnospermous pollen grain *Callialasporites trilobatus* (Balme 1957) Sukh Dev 1961 from the Brent Group (Middle Jurassic) of the northern North Sea. BGS specimen MPK 14718; 51 µm in diameter.

4. The bisaccate gymnospermous pollen grain *Alisporites* sp. from the Brent Group (Middle Jurassic) of the northern North Sea. BGS specimen number MPK 14719; 87 µm wide and 62 µm high.
5. The netromorph acritarch *Dorsennidium europaeum* forma *wenlockianum* (Downie 1959 ex Wall & Downie 1963) Sarjeant & Stancliffe 1994 from the Silurian of Wales. BGS specimen MPK 14723; 56 µm in diameter.
6. The angiosperm pollen grain *Gambierina edwardsii* Stover in Stover & Partridge 1973 from the Paleogene of the Sabrina Coast, East Antarctica (Smith et al., 2019). The diameter of this specimen is 35 µm. Scanning electron microscope image by Sophie Warny and reproduced with permission.

7. The dinoflagellate cyst *Senoniasphaera jurassica* Gitmez & Sarjeant 1972) Lentin & Williams 1976 from the Kimmeridge Clay Formation (Upper Jurassic [Tithonian]) of Warlingham, Surrey, southern England. BGS specimen MPK 1265; 89 μm long and 75 μm wide at the cingulum.
8. The dinoflagellate cyst *Oligosphaeridium complex* (White 1842) Davey & Williams 1966 from the Cromer Knoll Group (Lower Cretaceous) of the central North Sea. BGS specimen MPK 14587; the cyst body (which is subcircular in outline) is 50 μm in diameter
9. A representative of the chitinozoan genus *Ancyrochitina* from the Visby Formation of the Lusklint 1 section, Gotland, eastern Sweden (Silurian) (Vandenbroucke et al., 2013, fig. 5D). The overall length is 100 μm. Scanning electron microscope image by Thijs R.A. Vandenbroucke and reproduced with permission.

Table 1. A listing of the typical palynomorph spectra from the Proterozoic and Phanerozoic successions of the UK and adjacent areas, their potential for reworking into the soil profile, examples of relevant lithostratigraphical units and selected references. Generally, reworking potential increases with decreasing geological age because younger lithostratigraphical units generally have higher palynomorph concentrations. The Carboniferous and Cretaceous periods have been subdivided because of the substantial disparity in palynological productivity between their constituent epochs. The geochronological scale is taken from Gradstein et al. (2021). Certain lithostratigraphical units such as thermally-altered strata, highly oxidised/red-brown sedimentary rocks and highly crystallised and/or pure limestones are unlikely to release large numbers of palynomorphs into the soil profile due to their relatively organic-lean nature (Riding, 2021). In particular, geographically extensive units such as Lower Palaeozoic slaty mudstones, the Old Red Sandstone Supergroup, the Carboniferous Limestone Supergroup, the New Red Sandstone Supergroup and the Chalk Group of the UK are all organic-lean. There is, nonetheless, some variation. For example some Lower Palaeozoic and Devonian units are highly palyniferous, whereas palynomorphs are effectively absent throughout the Carboniferous Limestone Supergroup. Whereas some lithostratigraphical units are geographically widespread, others are local in distribution. The supergroups, groups and formations listed are generally southern UK-centric (Waters et al., 2007). For example, the Lower Cretaceous and Paleogene units are largely confined to southern England. Other major units which are of local extent are the Longmyndian Supergroup, and the Sleat, Stoer and Torridon groups; these are only present at outcrop in the

Welsh Borderland and northwest Scotland respectively. Similarly, the Cambrian through Silurian lithostratigraphical units mentioned are those that are found in the Welsh Borderland and the West Midlands of England. There are no widespread Neogene deposits in the UK (Boulter, 1971; Pound and Riding, 2015). Abbreviations: angio. = angiosperm; gymno. = gymnosperm; dino. cysts = dinoflagellate cysts; p. spores = plant spores.