An introduction to forensic soil science and forensic geology: a synthesis

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Abstract: Using forensic soil science and forensic geology as trace evidence and searches for burials is the theme of the papers in this Special Publication. The concept and design of this volume was initially established by the International Union of Geological Sciences, Initiative on Forensic Geology, which successfully brought together forensic geologists, forensic soil scientists, police officers and law enforcement agents in the investigation of crimes. In this introductory paper a brief overview is provided of the developments in interdisciplinary knowledge exchange with use of soil and geological materials (known as 'earth materials') in the search for burials and the provision of trace evidence. The aim is to provide background information on the role and value of understanding 'earth materials' ranging from the landscape scale, to the crime scene through to microscopic scale investigations to support law enforcement agencies in solving criminal, environmental, serious and organized crime, and terrorism. In this connection, recent advances in field and laboratory methods are highlighted. Finally, the 20 papers in the volume are briefly introduced and these include a diversity of global operational case studies that involve collection and analysis of earth material from crime scenes and searches for homicide graves and other buried targets.

This Special Publication contains 20 papers focusing on how information on soil and geological materials (also known as 'earth materials') has been used as trace evidence and in searches for burials. This information is required so that informed decisions can be provided to primarily aid and assist forensic soil scientists, forensic geologists and also police officers, law enforcement agents and forensic scientists with complex criminal and environmental investigations. The concept and design of this Special Publication was initially established by the International Union of Geological Sciences (IUGS), Initiative on Forensic Geology (IFG), which focussed on the following four topics: (1) background and importance for soil forensics and forensic geology; (2) ground searches for burials related to homicide, serious organized crime and counter terrorism; (3) trace evidence; and (4) research and development. The IUGS-IFG provided a forum for forensic soil scientists and forensic geologists to showcase the development of new, sophisticated field and laboratory methods and pioneering new search strategies, and to explore their experiences through the presentations of operational case study analysis.

This introductory paper has four objectives:

(1) To provide a brief overview of the recent (since 2000) interdisciplinary knowledge exchange between forensic soil science and forensic geology, and to explore the reasons why there has been a significant advancement on the applications of soil science and geology to the investigation of crimes.
(2) To provide background information to the role and value of earth materials in searches for burials and as trace evidence, ranging from the landscape and crime scene through to the microscopic scale, to help police and law enforcement in solving criminal,

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environmental, serious and organized crime and counter terrorism investigations.

(3) Highlight recent advances in new field and laboratory methods and operational casework from around the world, which demonstrates the breadth of soil forensic and forensic geology investigations now taking place.

(4) To explain the contents of the published papers in this Special Publication, which include a diversity of case studies involving the collection and analysis of earth materials from crime scenes and other items, and searches for homicide graves and other buried targets.

Forensic soil science and forensic geology are increasingly transdisciplinary, requiring researchers from many different scientific backgrounds to work together to answer many common questions in this rapidly developing field.

Origin of forensic soil science and forensic geology

The earliest published application of forensic soil science and forensic geology was in April 1856 (Science & Art 1856) when a barrel that contained silver coins was found on arrival at its destination on a Prussian railroad to have been emptied and refilled with sand. Professor Christian Gottfried Ehrenberg (1795–1876; Fig. 1) a natural scientist at the University of Berlin, acquired samples of sand from stations along railway lines and used a light microscope to compare the sand with the station from which the sand was most likely to have come from. This is arguably the very first documented case where a forensic comparison of soils was used to help police solve a crime (Fitzpatrick 2008). Professor Ehrenberg is considered the founder of both soil microbiology (a discipline of soil science; Blume *et al.* 2012) and microgeology (i.e. micropalaeontology, which is a discipline of geology) (Ehrenberg 1856).

A review of the historical developments of forensic geology, since the time of Professor Ehrenberg to present day rests beyond the scope of this publication. However, a detailed review was recently published by Donnelly & Murray (2021).

The need for the establishment of forensic soil science and forensic geology

This Special Publication explores the link between soil science and geology with *inter alia* forensic science. This book is one of the first attempts to specifically bring together researchers from disciplines as diverse as soil science and geology, and to involve forensic science. Disciplinary subgroups around topics such as pedology, geophysics, mineralogy, soil organic carbon and forensic science are well established in both academic and non-academic circles. However, connecting these disciplinary subgroups and establishing meaningful dialogue between them has proved difficult. There is a deeply embedded disciplinary isolation, in terms of journals, conferences, academic structures, policy and commercial frameworks, that acts unconsciously to restrict opportunities for lasting disciplinary crossover.

By 2000, increasing numbers of soil scientists and geologists around the world were applying their skills and expertise to assist the police and law enforcement agencies. This, undoubtedly, was also fuelled by TV documentary, film and media interest in 'forensics' and 'geology', which popularized these two disciplines, albeit often dramatized for media effect. However, as noted above, there was a degree of isolation between the various disciplines and subgroups. There was no or little research conducted, no conferences and workshops, few papers and publications. Importantly, there was no centralized, professional organization taking a responsible and formal lead for the development of forensic soil science and forensic geology. This was usually compounded by the often sensitive, confidential and high-profile nature of the criminal investigations

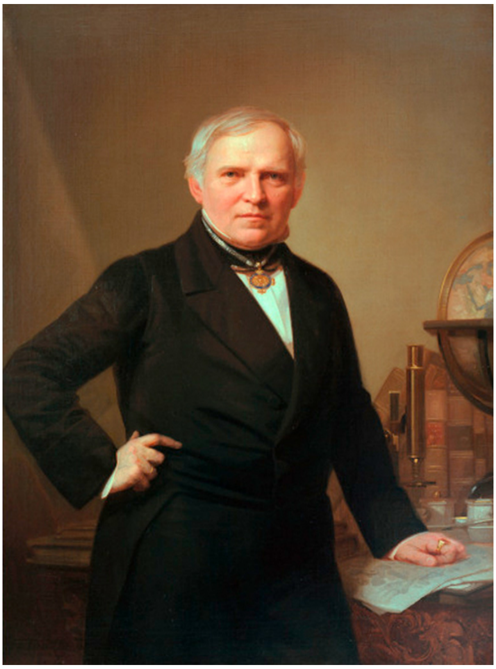

Fig. 1. Professor Christian Gottfried Ehrenberg (1795–1876). Painted by Eduard Radke in *c.* 1855 (source: https://en.wikipedia.org/wiki/Christian_Gottfried_Ehrenberg (in Donnelly *et al.* 2021).

that forensic soil scientists and forensic geologists support. However, this was about to change. In 2002, Dr Laurance Donnelly was invited to Westminster Palace, House of Commons in London, as part of the All-Parliamentary Group on Earth Science (Donnelly 2002*a*, 2002*b*, 2003). Here, he delivered a presentation on forensic geology and The Moors Murders. This was an infamous case in the UK in which two offenders, Myra Hindley and Ian Brady, abducted and tortured children before burying their bodies in shallow, unmarked graves, in the Pennine Hills, near Manchester. Since 1994, Dr Donnelly had been developing a new search strategy based on mineral exploration and engineering geology investigative methods (later to become known as the Geoforensic Search Strategy, GSS) to search for the last remaining victim of the Moors Murderers (the search is ongoing). The 2002 Westminster Palace event was followed by an interview on BBC Radio. Both events fuelled further interest amongst geologists, soil scientists, the media, police and politicians in applications of forensic geology to police and law enforcement investigations. From 2002 to 2005, Dr Donnelly worked on the establishment of a specialist group to focus on the development of forensic geology in the UK. In 2006, the Geological Society of London, approved the establishment of the Forensic Geoscience Group (GSL-FGG) (Donnelly 2005, 2006). In 2004, the first conference on forensic geoscience was held in London (Pye & Croft 2004; Donnelly & Ruffell 2017).

In 2006, the Centre for Australian Forensic Soil Science organized the 1st International Workshop on Criminal and Environmental Soil Forensics, which was held during the 18th International Symposium on the Forensic Sciences: Classroom to Courtroom, in Perth, Australia. The success of this international workshop gave rise to the organization of the following three Soil Forensics International (SFI) conferences in Edinburgh, UK (2007), Long Beach, California, USA (2010) and The Hague, Netherlands (2012). However, since 2012, it has become difficult to organize separate SFI conferences, largely because of the lack of any formal international network of forensic soil scientists.

Following the success of the establishment of GSL-FGG, which primarily had a UK focus, Dr Laurance Donnelly established in 2009 the IUGS Working Group on Forensic Geology (Donnelly 2008, 2009*a*, *b*), which was one of seven specialist groups in the IUGS Commission Geoscience for Environmental Management. This gave a fresh focus and brought global attention to the critical importance of cross-discipline communication and work in the diverse disciplines of soil science, geology and forensic science. This group ran successfully from 2009 to 2011 and held several forensic geology events around the world (Donnelly 2010*b*). It was subsequently elevated by the IUGS to the status of an ‘Initiative’. As such, the Initiative on Forensic Geology (IFG) was approved by the IUGS Executive Committee, at UNESCO Headquarters, in Paris, France, on 22 February 2011. The inaugural meeting of IUGS-IFG was held in Rome, Italy later that year on 19 September 2011 (Donnelly 2011). This also included a Geoforensic International Network (GIN), bringing together forensic geologists, geoscientists, forensic soil scientists and invited police and law enforcement officers from approximately 53 countries. The aim of IUGS-IFG is, ‘to develop forensic geology internationally and promote its applications’ (Fig. 2).

This global network of IUGS-IFG stakeholders includes geologists, geoscientists, forensic scientists, soil scientists, police officers, law enforcement agencies, engineers, mineral traders, lawyers, politicians, schools, universities, learned societies, public, journalists and the media. These have become aware of how information on earth materials can be used as trace evidence and in searches for burials so that informed decisions can be provided to support and help police/law enforcement officers/agents and forensic scientists with complex criminal and environmental investigations.

There has been a significant increase in the number of successful forensic geology events organized since the establishment of the IUGS-IFG. These include outreach, knowledge exchange and capacity building, and training. Many of these included were jointly organized with other organizations, including SFI and several scientific sessions at the 35th International Geological Congress symposium on Forensic Soil Science and Geology, held in 2016 in Cape Town, South Africa. In the 10 years from 2006 to 2016 there were at least 227 recorded events that focused on or included forensic geology and soil science (Table 1).

Basic concepts and terminologies used in forensic soil science and forensic geology

Forensic geology, also known more broadly as ‘forensic geoscience’ or ‘geoforensics’, may simply be defined as ‘the application of geology to policing and law enforcement, which may potentially be applicable to a court of law’ (Donnelly 2021; Ruffell & McKinley 2008). Forensic soil science and forensic geology include the science or study of soil and geological materials, which are also known as *earth materials*. Dr Murray has frequently used the term *earth materials* and illustrated how they contributed to solving complex cases from around the world in both his books on forensic geology (Murray 2004, 2011).

Fig. 2. Logos of the Geological Society of London (GSL), Forensic Geoscience Group (FGG) (upper), the International Union of Geological Sciences (IUGS), Initiative on Forensic Geology (IFG) (lower) (source: GSL and IUGS; FGG and IFG logos designed by Dr Laurance Donnelly).

Forensic soil science and forensic geology involve the application of soil science and geology, especially studies that involve soil–rock sampling and analysis, geomorphology, soil–geological mapping (assisted by existing soil–geological maps and spatially held data), hydrogeology, mineralogy, geochemistry, geophysics, palaeontology, biology, palynology and molecular biology to answer legal questions, problems and hypotheses (e.g. Pye 2007; Fitzpatrick 2008, 2013*a*, *b*; Ritz *et al.* 2008; Ruffell & McKinley 2008). In many scenarios, a robust understanding of some of the basic concepts and terminologies of forensic soil science and forensic geology is required to assess how information on *earth materials* has been used as trace evidence and furthermore, to identify the geological and geographical provenance of *earth material* samples to assist with searches for burials. This information is required so that informed decisions can be made to support and help police, law enforcement and forensic scientists with criminal investigations. To illustrate the basic concepts and terminologies a series of images and descriptive diagrams based on previously completed, forensic, operational case studies is provided below.

What are geological and soil materials (earth materials)?

Geologists and soil scientists (in particular, pedologists, from the Greek pedon, meaning ‘soil’) are often concerned primarily with understanding the variety of geological and soil materials, respectively, and their characteristics, properties and distribution. This is most directly focused on the key questions concerning sampling, descriptions, processes of soil and geological material formation, including the quality, extent, distribution, spatial variability and interpretation from microscopic to megascopic scales. The description and interpretation of soil and geological materials can be used in addressing questions, such as, ‘What is in soil and geological materials?’ or ‘Where did soils and geological

Table 1. *A selection of key events that led to the establishment and development of: (a) Geological Society of London, Forensic Geoscience Group (FGG), (b) the International Union of Geological Sciences (IUGS) Working Group on Forensic Geology (2009–2010), (c) the Geoforensic International Network (GIN) and (d) the IUGS Initiative on Forensic Geology (IFG)*

Year	Location	Key event
2016	Cape Town, South Africa	35th International Geological Congress: joint Soil Forensics International (SFI) and IFG Symposium on Forensic Soil Science and Geology in association with the 5th SFI conference
2012	Brisbane, Australia	34th International Geological Congress: IFG Forensic Geoscience Symposium and 2 day workshop for police on ‘Design, Management and Implementation of Ground Searches using Geophysical Equipment’
2011	Rome, Italy	Inaugural Meeting of the IUGS-IFG
2011	Paris, France	Establishment of the IUGS-IFG
2010	London, UK	Conference of the Geological Society of London, Forensic Geoscience Group, ‘Environmental and Criminal Geoforensics’
2010	Long Beach California, USA	2nd SFI conference
2009	Manchester, UK	Establishment of the GIN, as part of the IUGS Working Group on Forensic Geology.
2009	Montevideo, Uruguay	Establishment of the, IUGS, Geosciences for Environmental Management, Working Group on Forensic Geology
2009	Bogota, Colombia	1st Ibero-American Congress on Forensic Geology, Universidad Nacional de Colombia, National Institute of Medical and Legal Geology, Bogota, Colombia
2008	London, UK	Conference of the Geological Society of London, Forensic Geoscience Group, ‘Geoscientific Equipment and Techniques at Crime Scenes’
2008	Knoxville, Tennessee, USA	Exploratory investigations at the University of Tennessee, Department of Forensic Archaeology (The Body Farm), and Manchester, UK. A search for the last remaining victim of the Moors Murders using geological exploration and engineering geology techniques and the detection of leachate and volatile organic compounds
2007	Edinburgh, UK	1st SFI conference
2006	London, UK	Inaugural conference of the Geological Society of London, Forensic Geoscience Group: ‘Geoscientist at Crime Scenes’
2006	Perth, Australia	1st International Workshop on Criminal and Environmental Soil Forensics, at the 18th International Symposium on the Forensic Sciences: Classroom to Courtroom, Perth, Australia. Centre for Australian Forensic Soil Science
2002–2006	London, UK	Establishment of the Geological Society of London, Forensic Geoscience Group
2003	London, UK	Conference on, ‘Forensic Geoscience: Principles, Techniques and Applications’. The Geological Society of London
2002	London, UK	BBC Radio interview on Forensic Geology for ‘Material World’
2002	London, UK	Meeting and presentation on, ‘Forensic Geology and The Moors Murders’. All-party Parliamentary Group for Earth Science, Westminster Palace, House of Commons, London, UK
1994–2002 (and ongoing)	Manchester, UK	Search of Saddleworth Moor, UK, for the last remaining victim of the Moors Murders

Note: GSL-FGG, IUGS Working Group on Forensic Geology, IUGS-GIN and IUGS-IFG were established by Dr Laurance Donnelly to advance the applications of geology to the police and law enforcement. The IUGS-IFG continues to promote and develop forensic geology with an international focus, including crime scenes examination, geological trace evidence, ground searches for burials, environmental crimes and crimes that take place in the minerals, mining and metals industries. In the 10 years from 2006 to 2016 there were at least 227 recorded events that focused on or included forensic geology (source: Donnelly & Murray 2021).

materials originate from?’ (i.e. provenance determination, also known as ‘geolocation’).

This may be required, for example, in criminal investigations relating to the characterization and location of the sources of earth materials to make forensic comparisons. However, the shift from traditional soil science and geology to forensic soil science and forensic geology, respectively, is not straightforward and requires the acquisition of additional skills by the soil scientist or geologist. This requires a detailed understanding of crime scene protocols, the collection of earth materials as physical evidence, the evidential requirements of forensic workers, reporting, giving evidence on court and the nature of legal constraints within which forensic work takes place, as emphasized by Kobus & Robertson (2019). These skills are not traditionally part of the training received by conventional soil scientists and geologists. As such, they have to be gained by formal training and operational case work experiences.

Forensic soil scientists and geologists recognize and quantify differences between various types of earth materials and understand how these differences can be used in making comparisons between earth materials found at crime scenes or on evidential objects or items seized by the police or law enforcement. Earth materials can differ in colour, particle size distribution or texture, in the way the individual particles are arranged. Earth materials can also be cemented to form complex shapes of particles or peds, or vary in the amount and type of organic matter. Furthermore, earth materials may have a complex of variable mineralogy, inorganic or anthropogenic particles. Specifically, it is important to understand and know the different kinds of natural and human-made (anthropogenic) soil and geological materials, and how they form and especially how to carefully describe, sample and analyse them because this helps make accurate forensic comparisons.

Pedogenic systems differ from geological ones in that the latter are generally static while the former are dynamic. Hence, an important feature of soil materials is that they are not static but comprise a dynamic natural process, which interacts in a complex manner with the environment. For example, soil materials can change through time and in space, as a response to environmental changes, such as from agriculture (Fig. 3) and bushfires (Fig. 4). As a result of this, soil materials will show variation at different times within the development of a landscape, as shown in Figures 3 and 4. The potential three-dimensional variability of soil materials, from location to location, at any given time is of considerable importance to forensic soil science. For example, the differences between the undisturbed natural soil under native vegetation with high organic matter content and adjacent disturbed farmed soil occur gradually over a distance of *c.* 1 m, as shown in Figure 3. In contrast, burnt soil materials following a bushfire show abrupt and marked differences, which may occur at the micro-scale within millimetres, as shown in Figure 4. Taking this argument to its extreme conclusion, we might therefore consider that no two places on the Earth’s surface have identical earth materials.

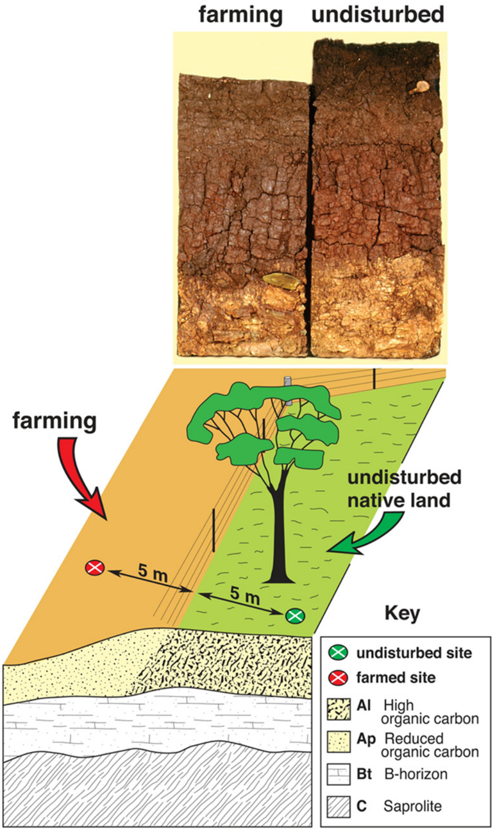

Fig. 3. Photographs of two adjacent exposed soil profiles showing abrupt changes in the near-surface soil properties between undisturbed natural soil under native vegetation with high organic carbon and disturbed eroded farmed soil.

To determine the wide variety of earth materials that occur in the world, it is necessary to understand the soil and geological classification systems used to illustrate this. For example, similar to the grouping or naming of rocks and minerals (e.g. Bobrowsky & Marker 2018*a*, *b*, *c*), soil classifications help organize knowledge about soils, especially in conducting soil surveys (e.g. Wilding 1994). The two international soil classification systems that are used widely are the World Reference Base (WRB) (IUSS Working Group WRB 2015) and Soil Taxonomy (Soil

Fig. 4. Photograph of manufactured earth materials comprising brick paving, mortar (mixture of cement, fine sand and lime) and adjacent transported organic-rich garden soil (modified from Raven *et al.* 2019).

Survey Staff 2014). Many countries also have national and specialized technical classifications (Fitzpatrick 2013*d*). Soil surveys enable the depiction of soils across a landscape and soil maps are made to show the patterns of soils that exist and provide information on the properties of soils (e.g. Fitzpatrick & Raven 2012; Stern *et al.* 2019). Soil maps are produced at different scales to depict soils over: (1) large areas such as the world, countries and regions (1:100 000 scale or smaller scale); and (2) detailed areas such as farms (1:10 000 scale or larger scale). A wide diversity of natural soils exists and each has its own characteristics (e.g. morphology, mineralogy and organic matter composition). For example, according to the United States Department of Agriculture, which collects soil data at many different scales, there are over 50 000 different varieties of soil in the USA alone! Parent material, climate, organisms and the amount of time it takes for these properties to interact will vary worldwide.

Numerous types of earth material are excavated to supply raw materials for engineering construction, such as the building of dams, bridges, roads, tunnels and structural foundations. Other raw materials are mined for landscaping of industrial and urban sites such as the ingredients used for bricks, mortar (mixture of cement, fine sands and lime), ceramic products and transported organic-rich garden soil, as shown in Figure 4.

Most transportation networks and urban communities are built on soils (i.e. human-made soils). Human-made soils, also known as ‘anthropogenic soils’, are called Technosols in the WRB, and as human-altered and human-transported soils in Soil Taxonomy (Soil Survey Staff 2014). These types of soils are characterized by diversity, heterogeneity and complexity, which enables forensic soil examiners to better distinguish between them. They are generally characterized by a strong spatial heterogeneity, which results from the various inputs of exogenous materials (e.g. compost, minerals, technological compounds and inert, organic or toxic wastes) and the mixing of the original (natural) soil material (e.g. parks, gardens, landscaping and cemeteries). Mine or quarry soils are another class of human-made soils, which are also strongly influenced soils, although usually found away from cities. Human-made soils (e.g. Fig. 5b, c) typically contain ecological heterogeneity and show a special distinctness of soil properties. These specific soils also contain a large array of historical information, which has been proved useful in understanding and quantifying soil differences in forensic soil comparisons (Fitzpatrick & Raven 2012; see Fig. 6c).

The major question posed is how can earth materials be used to make accurate forensic comparisons when we know that both natural and human-made earth materials are highly complex and that there is an unlimited number of different types of earth materials in existence? The following key issues are especially important in forensic earth material examination because the diversity of soils and geology strongly depends on topography and climate, together with anthropogenic contaminants:

- Forensic earth material examination can be complex because of the strong diversity and heterogeneity of earth material samples. However, such

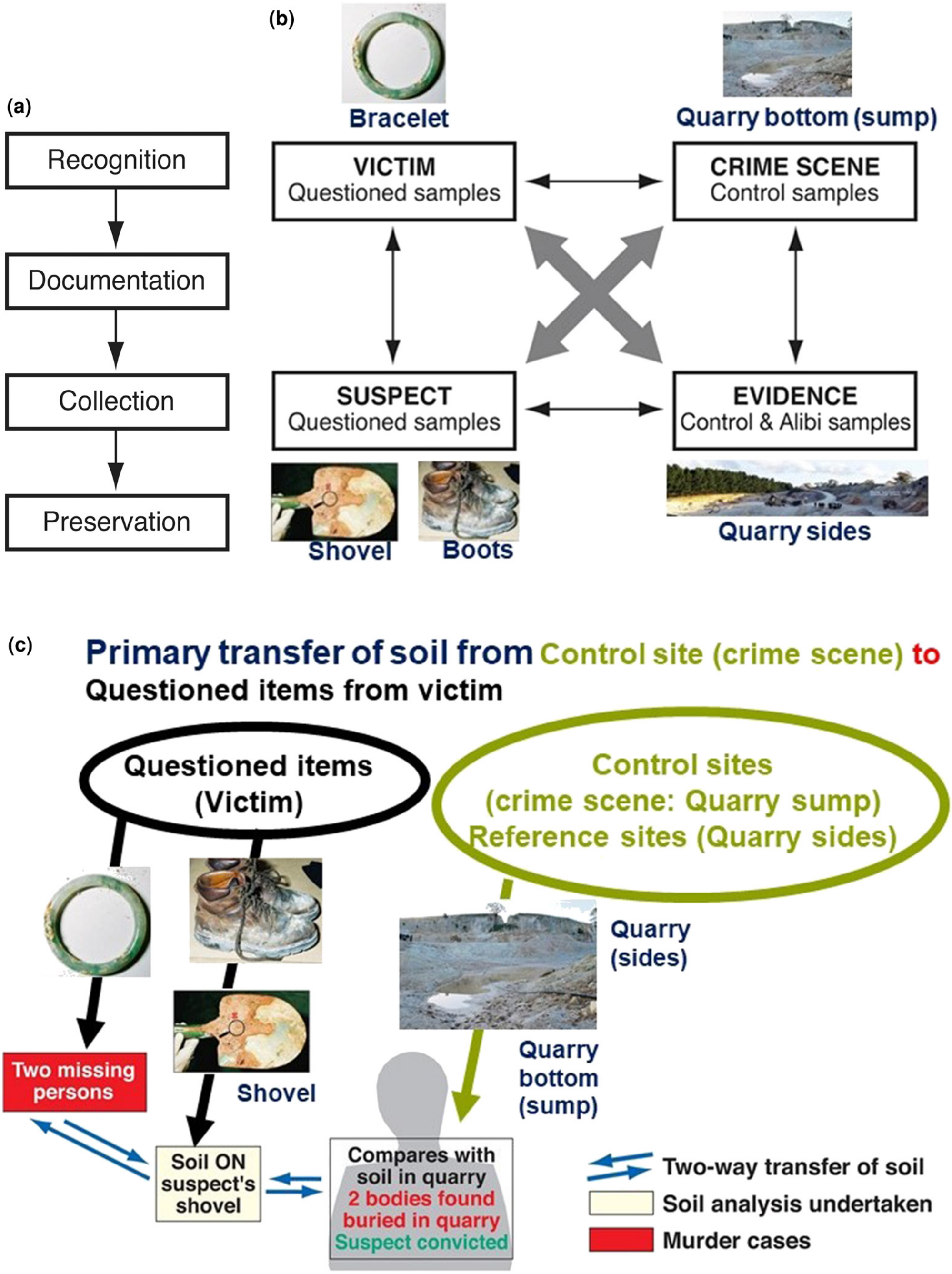

Fig. 5. Schematic diagrams illustrating: (**a**) the correct sequence for conducting forensic investigations involving earth materials; (**b**, **c**) the *primary transfer* of earth material from known control 'collected' sampling sites at the crime scene (i.e. sump in quarry) to questioned earth materials on items that are linked to the suspect (i.e. shovel and boots) and victim (i.e. bracelet) using a two or four-way linkage and (b, c) known reference sites (e.g. quarry sides) or alibi sites. Reference earth material sites/areas from soil maps, geological maps and earth materials in archive collections were also used to assist in making earth material comparisons (modified after Fitzpatrick & Raven 2012).

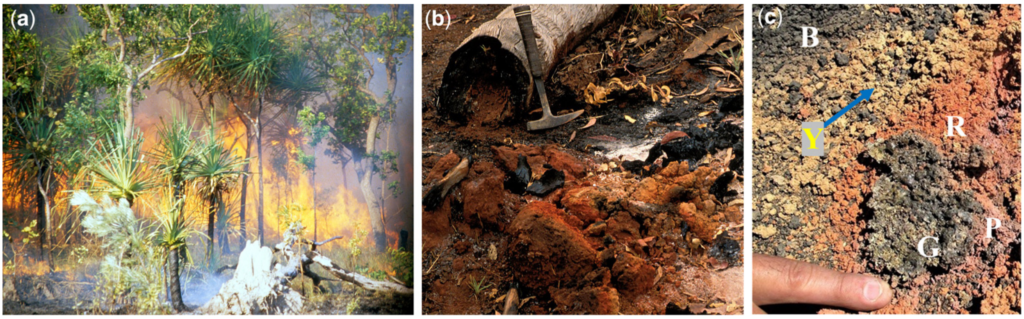

Fig. 6. Photograph of burnt earth material following a bushfire showing different coloured minerals formed under a range of temperatures, including: B, black, partly burned powdery earth material with charcoal fragments on the soil surface (80°C) with pyrite, goethite, kaolinite, smectite and mica; Y, yellow, strongly burned friable earth material (c. 500°C) with maghemite, mica and amorphous silicates; R, red-purple, severely burned brick-like soil (700–900°C) with hematite, mullite, mica and amorphous silicates; P, purple, severely burned brick-like earth material (900–1000°C) with hematite, mullite and amorphous silicates; G, dark grey extremely burned fused and melted earth material (1000°C) with amorphous silicates, akermanite and gehlenite.

diversity, heterogeneity and complexity enable forensic examiners to distinguish between samples, which may appear similar to the untrained observer.

- A major problem in forensic earth material examination is the limitation in the discrimination power of the standard and non-standard procedures and methods.

Earth materials may also include mixtures of rock fragments, microfossils, natural soils and human-made materials made from earth raw materials (e.g. bricks, bitumen, concrete, tiles, plasterboard, glass and corrosion products from infrastructures such as wire fencing). As such, earth materials are highly individualistic in that there is an almost infinite number of different types. Furthermore, they may change rapidly over very short distances both horizontally and vertically (Figs 3 & 4), nationally and internationally. This enables forensic examiners to distinguish between earth material samples. For example, the following diverse range of human-made or anthropogenic materials have been added to both rural/farmed soils (e.g. cultivated for decades as shown in Fig. 3) and urban soils:

- High amounts of corroded iron particles from the wearing out of plough shears/tillage points owing to the highly abrasive nature of some Australian soils (Fitzpatrick & Riley 1990).
- Corrosion products from wire fencing materials.
- Brick (Raven *et al.* 2019) and concrete particles.
- Soil additives from fertilizers, lime or gypsum.
- Soil additives containing mixtures of sand, bark, perlite, scoria or coco coir.
- Black powdery charcoal, yellow friable, red brick-like, purple brick-like and dark grey coloured fused/glassy soil materials, which have formed under a range of temperatures such as in severe bushfires to cause permanent conversion of some soil minerals into new minerals (Fig. 4).
- Burnt bone and teeth fragments (Smith *et al.* 2017; e.g. from human, livestock or wild animals) that, during intense bushfires are permanently transformed into a crystalline structure.

It should also be noted that soils may contain pollen, which, when sampled and analysed by an experienced forensic palynologist could provide information in support of or in addition to mineralogical evidence or to corroborate case intelligence (Wiltshire & Black 2006; Wiltshire 2009, 2010, 2015; Wiltshire *et al.* 2015).

Earth materials providing trace evidence in criminal investigations

The following provides an overview to the role and value of earth materials as trace evidence in solving criminal investigations.

Theory of transfer of soil materials from one surface to another as a result of contact

The transfer of trace evidence is governed by what has become known as the *Locard Exchange Principle* (Locard 1930); this is based on the premise that when two surfaces come into physical contact there is the potential for mutual transfer of material between them. This transfer of material may be short lived or beyond detection but has taken place. Earth materials are routinely observed on the surfaces of items and objectives such as vehicles or shoes and clothing used as evidence by police, crime scene investigators and forensic scientists.

Primarily, such earth material evidence must be recognized on all possible items relating to an investigation (Fig. 6a). Secondly, the earth material evidence must be well documented. Finally, meticulous collection and preservation of earth material samples must be maintained in order to preserve the integrity of the earth materials (Fig. 6a), followed by earth material characterization primarily in the laboratory.

Although the forensic characterization of earth material is primarily performed in the laboratory, it is emphasized that earth material analysis typically begins with the sampling and description of four distinct groups of samples, which are categorized as follows:

(1) *Questioned sample:* the origin is unknown or disputed, often from a suspect or victim. These samples are collected from a suspect or victim or may be earth materials that have been transported by a shovel, vehicle or shoes (Fig. 6b).
(2) *Control sample:* the origin is known, often from sites such as the crime scene (Fig. 6b).
(3) *Reference sample:* the origin or type is known. Such samples may comprise samples collected from (a) known sites linked to a victim (e.g. soil collected from a road verge outside the victim's house or in an area adjacent the crime scene, such as the side of quarry; Fig. 6b) and/or (b) reference samples held in a museum or soil/geological archive (e.g. dinosaur nest materials). Reference soil sites/areas from soil or geological maps can also be used to assist in making soil comparisons (Fitzpatrick & Raven 2012).
(4) *Alibi sample:* the origin is known and that provides a measure of the distinctiveness of the questioned and control samples, thereby providing a more comprehensive analysis of the targeted comparator samples to provide a more accurate representation of the heterogeneity of the crime scene (e.g. soil collected from the sides of the quarry as shown in Fig. 6c or from the backyard or driveway of a suspects home).

The aim of forensic analyses of earth materials is to associate soil, rock particles or mineral samples taken from a questioned item, such as shoes, clothing, shovels or vehicles and earth materials from a known item with a specific location or common origin (control site). The role of the forensic soil scientist or forensic geologist is to determine if there are unique features of earth materials crucial to an investigation that enable the questioned earth materials to be compared with earth materials from known locations (i.e. control, reference or alibi samples). Earth material samples must be carefully collected and handled using established sampling protocols or a Standard Operating Procedure (SOP), if available (e.g. Fitzpatrick & Raven 2016; Donnelly 2020) and then examined by a forensic soil scientist or a forensic geologist who is suitably qualified and appropriately experienced. In particular, they should be competent in forensic science to ensure that the earth material samples can be formally used during an investigation and reported then presented as physical evidence to court, if required.

Knowing how many questioned, control (e.g. possible scene of a crime), reference (e.g. victim's house) and alibi (e.g. suspect's house) samples to collect is often difficult. The number, size and type of samples to be taken are strongly dependent on the nature of the environment and crime scene being investigated, especially the type of soil (e.g. wet or dry soil) and the nature of activity that may have taken place at the sampling location (e.g. suspected transfer of soil from the soil surface only or from a depth in the case of a buried object or body, or both). Usually the number of samples should never be less than three, preferably at least five. Large or more variable crime scenes will require a larger number of samples (e.g. a complex scene could require more than 50 samples). However, the main purpose in all forensic soil science and geology investigations is to collect a set of samples that are representative and unbiased.

The role of the forensic soil scientist or forensic geologist is to compare materials from these three groups of samples and draw conclusions about the origins of the questioned earth material samples. Earth materials are being recognized and used in forensic investigations to associate an earth material sample taken from an item, such as a victim's clothing (questioned earth material), with earth material from a specific known location such as the crime scene (control earth material). For example, the exchange can take the form of earth material from a location transferring to clothing of a person who walked through a particular area (e.g. Morgan & Bull 2007; Morgan *et al.* 2009; Murray *et al.* 2016, 2017). These types of transfers are referred to as *primary transfers* (McDermott 2013). In the example provided in Figure 6c, evidence was transferred from the earth material in the bottom of the quarry to the suspect's boots and shovel and also to the victim's bracelet. This was subsequently recovered from the boots (in the treads of the sole and on the surface of the boots) and on the shovel (Fitzpatrick & Raven 2012).

Once a trace material has transferred, any subsequent movements of that material are referred to as *secondary transfers*. For example, reddish-brown soil was transferred to a victim's vehicle from driving on muddy forest service roads (*primary transference*; Fig. 7). The reddish-brown soil was subsequently transferred to the suspect's jacket (questioned earth material and *secondary transference*) when he brushed up against the dried mud on the victim's vehicle when breaking into the vehicle (Fig. 7). These secondary transfer materials can also be significant in evaluating the nature and source(s) of contact (e.g. break-in to vehicle). As such, the conclusive comparison between the reddish-brown soil on the victim's car and the suspect's jacket provided information linking the person to the crime scene. Higher-order transfers (*tertiary transfers*) of trace evidence can also occur, which can present interpretative problems for forensic soil scientists and forensic geologists because the original source of trace evidence may be extremely difficult to identify (Fitzpatrick 2013*a*, *b*).

In substitution cases (also known as 'saltation'), criminals frequently substitute goods in shipment with other materials to mimic the weight of the goods, but of a lower value. This is particularly common in the international trading of mineral concentrates. These crimes can be controlled by well-organized criminal networks or cartels that gain financially. In most cases, the timing and location of substitution is unknown. However, the use of minerals, rocks or soil as substitution 'ballast' can provide investigators with valuable information, such as the geographical or geological provenance of the materials used as a substitute. As noted above, this was successfully demonstrated by Professor Christian Gottfried Ehrenberg in 1856 (Science & Art 1856) and other examples of 'substitution cases' can be found in Salvador *et al.* (2019), Murray (2011) and Murray & Tedrow (1975). During an investigation a consignment of base metal mineral concentrate was produced from a mine and processing plant in South America. When the material was transhipped and arrived at destination in Asia the assay results showed there to be a relative reduction in the amount of copper metal present. This was investigated using the automated mineralogy technique, 'Quantitative Evaluation of Materials by Scanning Electron Microscopy' (QEMSCAN). Reserve samples of the material in South America and China were analysed and the results showed a distinct increase in the amount of iron minerals in the samples from Asia, in comparison with the samples from South America. Furthermore, these iron minerals were angular to subangular and contrasted with the more rounded and spherical mineral particles that had been

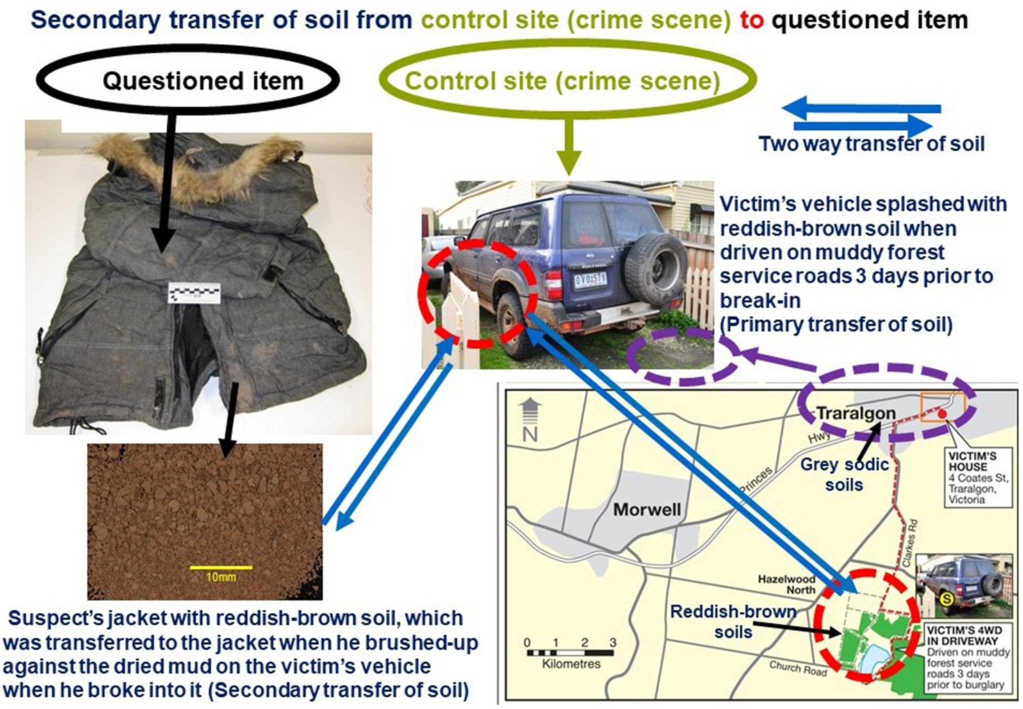

Fig. 7. Schematic diagram illustrating the *secondary transfer* of reddish-brown soil to the suspect's jacket (questioned soil) when he bushed up against the dried mud on the victim's vehicle (known control soil), which originated from driving on muddy forest service roads 3 days prior to the break-in to the vehicle (primary transfer of soil; Fitzpatrick 2013*c*).

subjected to processing. The addition of the iron minerals caused a relative lowering of the payable copper minerals and therefore a potential financial loss to the buyer. Whilst it is possible that the iron minerals resulted from cross-contamination, the more likely cause was adulteration to reduce the value of the mineral cargo (Donnelly & Ruffell 2021; Fig. 8).

In summary, analyses of earth materials is an emerging multidisciplinary science that can deliver powerful forensic evidence with significant benefits to criminal investigations (Pye 2007; Ritz *et al.* 2008; Ruffell & McKinley 2008; Fitzpatrick & Raven 2012, 2019; Raven *et al.* 2019).

Counter terrorism investigations for national security

Earth materials can potentially provide powerful, perhaps ideal, contact trace evidence that assists in criminal investigations for the following reasons as outlined by Fitzpatrick (2013*a*, *b*):

1. Earth materials are highly individualistic in that there is an almost infinite number of different types. Earth materials change rapidly over very short distances, both horizontally and vertically, enabling forensic soil scientists and forensic geologists to distinguish between samples. The human-made or anthropogenic properties (e.g. additions of brick or glass fragments) make the naturally occurring earth materials even more individualistic.
2. Fine clayey mud and fine sand size fractions of earth materials may be cohesive and have a strong capacity to transfer and stick to shoes or clothing.
3. Unlike the more obvious transfer of coloured, non-earth materials, such as blood, lipstick smears and paint, which are relatively more easily visible and identifiable, earth materials are nearly invisible to the human eye or to those not trained and experienced in their detection. For instance, fine-textured earth materials, especially when they impregnate vehicle carpeting, shoes or clothing, are often not visible to the naked eye, and so a suspect will often make little effort to remove them. What is more, some earth material particles may remain after cleaning.
4. A suspect or offender may be forensically oblivious to the potential value of earth materials as providing physical evidence to link him/her with a crime scene, item, object or geographical location.
5. Earth materials are easily located and collected using hand lenses or light microscopes when inspecting crime scenes or examining evidence.
6. Earth materials are easily described and characterized by colour and by using various analytical methods such as X-ray diffraction (mineralogy) and spectroscopy (chemistry). For example, the colour of a soil indicates its origin as well as the compounds present in the soil. White or grey soil may contain lime or have been leached, while black or grey soil indicates that the soil contains organic materials or moisture respectively. Red, brown or yellow soil usually indicates the presence of iron compounds. It should be noted that some soil samples may degrade by weathering, resulting in the deposition of secondary minerals in the time elapsed since they were collected from the crime scene or seized object/item.
7. Digitized soil and geological maps and soil profile, mineralogical and geochemical databases and geographical information systems (GIS) can be readily accessed by police or forensic scientists through the internet, e.g. Australian Soil Resources Information System database (Johnston *et al.* 2003) and the online geological database freely available from the British Geological Survey.

As noted above, the presence of human-made materials (e.g. additions of brick particles, glass fragments or corroded iron particles) makes the naturally occurring earth materials even more individualistic (e.g. Fitzpatrick 2013*a*, *b*). Mixtures of natural and human-made earth materials are common and pose significant challenges to determine all of the sources, provenances and significance of the trace evidence. Exhibits (e.g. footwear, clothing, vehicles) from which earth materials may be recovered are likely to have been used in multiple locations before, during or after the forensic event, resulting in samples containing earth materials of multiple provenances that need to be compared with a single source location sample (e.g. Fitzpatrick 2013*a*, *b*, *c*; Fitzpatrick & Raven 2016). For example, the samples recovered from shoes used by a suspect to run between different sites are shown in Figure 9 (Fitzpatrick *et al.* 2009) and are subject to the following number of variables from each site visited by the suspect:

1. Human-made soil types from earth materials on the bitumen road.
2. Natural soils from (a) the clayey steep side of the riverbank, (b) the stony riverbank, (c) the submerged mud in the river and (d) park land under tree vegetation.
3. Soil material condition (i.e. wet/dry, compact or loose).

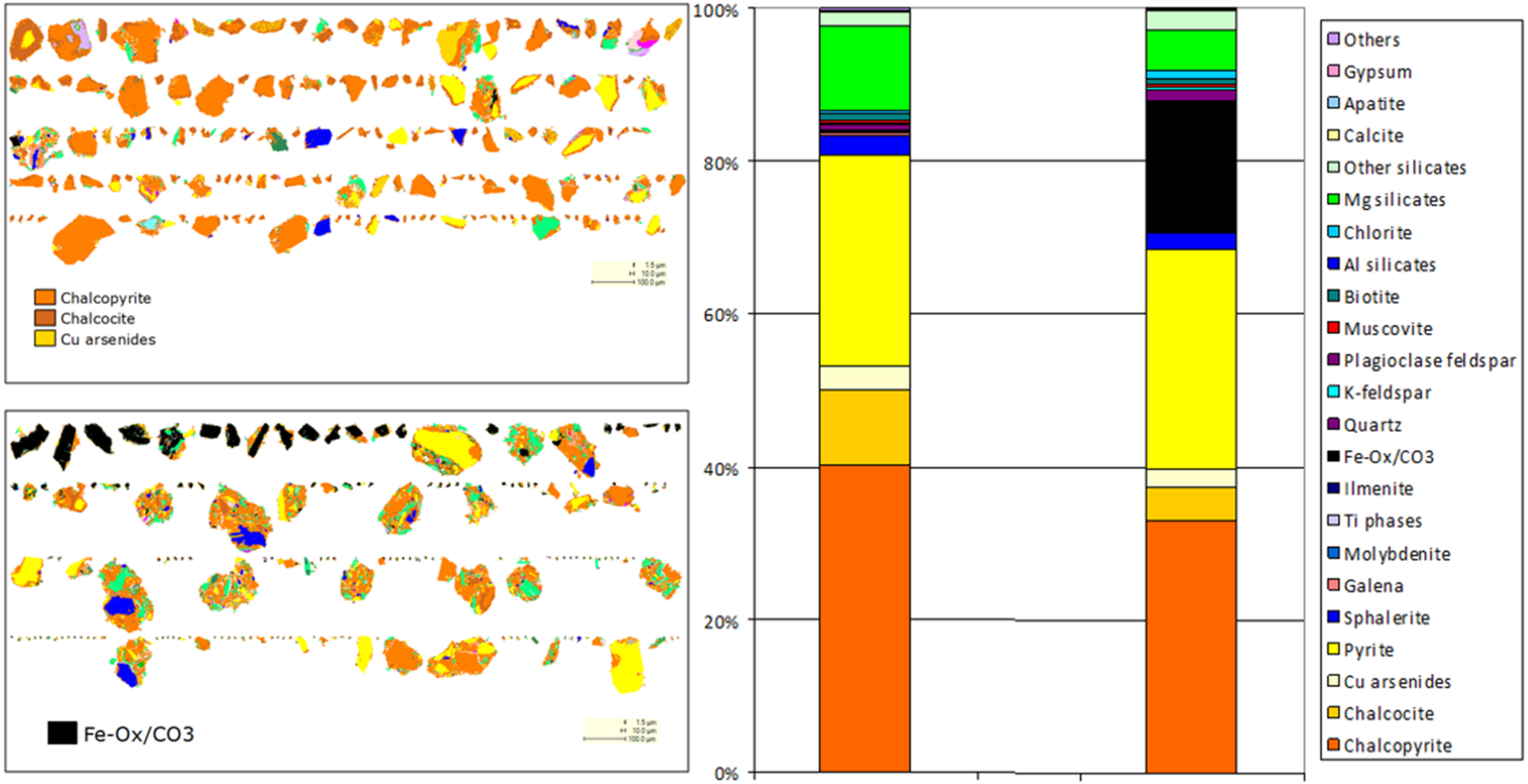

Fig. 8. QEMSCAN analysis for sample A (left, upper) and sample B (left, lower). The latter indicates increased amount of iron oxides potentially from adulteration of the samples prior to analysis. Data are also shown graphically (right), where the left column represents loadport material and the right column the disport material (source: Laurance Donnelly; QEMSCAN by Duncan Pirrie, in Donnelly & Ruffell 2021).

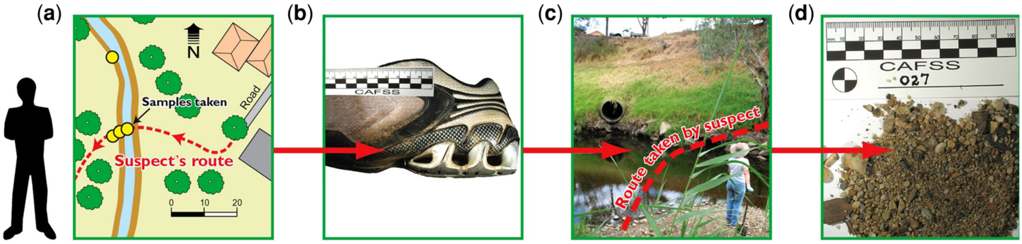

Fig. 9. (**a**) Schematic map showing the locations, aspect and path taken by suspect after leaving the scene of a fatal car collision (a 'hit and run' case; Fitzpatrick *et al.* 2009), showing (i) bitumen road alongside houses, (ii) park land under tree vegetation (western side), (iii) steep riverbank (western side), (iv) location where susptect walked or ran through/across the river, (v) gravely and stony flat river bank, (vi) steep river bank (eastern side), (vii) parklands under trees (eastern side). (**b**) Sole tread of shoe worn by the suspect containing soil (questioned sample). (**c**) Overview of the stream and steep river bank, person standing at point where the control soil sample was taken (i.e. near where a shoe impression matched the shoe). (**d**) Sample of control earth material.

(4) Transfer and persistence from (a) footwear and clothing, (b) the depth of tread on the footwear, (c) the particle size of the soil, (d) the number of scenes frequented and (e) the movement type and speed (walking, running and jumping into the river).

(5) Soil sample preparation (i.e. storage conditions – wet or dry).

However, many operational (real-world) forensic cases that encounter trace soil evidence, especially if small amounts of human-made particles and/or mixed provenance samples are present, further complicate the issue of interpreting mixed source samples. Furthermore, the ability to identify mixed source samples from exhibits such as vehicles and footwear, as shown in Figure 9, which may have made contact with multiple locations, is key to making robust interpretations that may be of investigative and/or evidential value in forensic investigations.

Such cases cannot be easily resolved based solely on the use of current 'standard techniques', which mostly involve soil morphological observations (e.g. visual soil colour determinations using the Munsell Soil Color Book 2009, and other descriptive soil features; McDonald and Isbell 2009; Schoeneberger *et al.* 2012) and standard laboratory analyses of the mostly inorganic components in soils (e.g. X-ray diffraction analyses; Kugler 2003; Fitzpatrick 2013*a*, *b*; Fitzpatrick & Raven 2016). Consequently, state-of-the-art analytical techniques are often required to enhance the current traditional forensic soil analyses methods to better quantify mixtures of natural and human-made soils to locate potential crime scenes or burials (e.g. shallow, unmarked, homicide graves) and discriminate between crime sites, link suspects and/or objects to crime scenes or locations and trace the origin of materials (e.g. Fitzpatrick & Raven 2019; Raven *et al.* 2019).

Increased performance in instrument sensitivities and detection capabilities will provide practitioners with high resolution and timely analyses at greater resolution, accuracy and precision. Recent advancements in new instrument technologies presented in this volume (Fitzpatrick & Raven 2019; Raven *et al.* 2019) have created an opportunity for higher-resolution analysis of earth materials leading to new forensic insights and capabilities. However, the need to establish the validity of such new, innovative and state-of-the-art analytical techniques employed within forensic science has been highlighted in several forensic and Law Commission Reports (Report to the President 2016). In addition, field portability in some applications is also critical (e.g. Bergslien 2019).

The role and of earth materials in searches for burials

The use of earth materials to assist with a search is sometimes referred to a 'predictive geolocation' or 'provenancing' (Donnelly & Harrison 2013, 2015, 2020, 2021; Pirrie *et al.* 2017). This may be carried out to see if there is an association of earth material trace evidence between an item and an offender/suspect. As noted above, this is by no means new; the first formally recorded case in forensic geology and soil science was in the latter part of the nineteenth century whereby Professor Christian Gottfried Ehrenberg, as noted above, assisted the police in the investigation of stolen silver being transported on a train in Prussia. He was able to predict the likely geographical source of the sand used in the substitution, which proved to be a breakthough in the case.

Questioning where earth materials originated in a criminal investigation was also used in practice by

Edward Heinrich, who was working at Berkeley, the University of California, in the 1920s. Heinrich used sand grains recovered from a small knife to locate the body of Father Patrick Heslin, who had been kidnaped by William Hightower, later found guilty. He also used sand grains to assist in a case where an ear was found from a dismembered body belonging to Mrs Sidney d'Asquith. He was able to determine that the sand was not consistent with the marsh where the ear was found, but the associated salt crystals suggested an estuarine origin. This provided suggested search areas and the use of topographic maps resulted in the discovery of the remainder of the body parts near the mouth of San Leandro Creek, some 12 miles from where the ear was found.

Microfossils, including spores, shells and foraminifera, may be particularly useful to identify a search area, especially if they have a limited biostratigraphical range within a sedimentary sequence of strata and a restricted geographical distribution. In a more recent case in the UK, the analysis of soil containing chalk fragments found microfossils, which was significant in the case of two murdered school children (Bailey *et al.* 2017).

The value of earth materials in determining a possible search area may not necessarily be obvious to an investigating police or law enforcement officer. The authors are aware of missed opportunities where soil has been disregarded or its potential relevance not recognized. This suggests the need for training and raising awareness of geolocation and earth material provenancing within law enforcement.

Earth materials could be present on a victim, offender, clothing, weapons, shoes/boots, spade or other digging implements. These should be inspected to determine if they contain deposits of geological materials transferred from a burial site. Footprints might also be considered if they contain any geological materials from another location or search area.

The earth materials will require careful collection consistent with standard forensic best practice (Pirrie *et al.* 2017; Donnelly 2020) followed by analysis by a suitably qualified and experienced forensic soil scientist or forensic geologist (mineralogist) (Fitzpatrick & Raven 2016). The results of the analysis might be able to suggest a search area, particularly if law enforcement has other corroborative evidence, such as an eye witnesses, closed circuit television, automatic number plate recognition or mobile phone data. Apart from in rare circumstances, where there unique or exotic geological materials are detected, it is unlikely that the analysis will identify the precise location of a burial. More likely, the results will delineate a general search area or suggest a new search area, which was not previously considered.

Using earth materials to identity a search area is only possible if there are readily available, high-quality, large-scale published geological or soil maps and, as noted above, geological databases. Many are now accessible from national geological or soil surveys and some can be quickly acquired from a mobile phone, see for example the British Geological Survey's 'iGeology' app or the Tellus database available from the Geological Survey of Northern Ireland. This is a national programme to collate geophysical and geochemical data for soils, rocks and water (e.g. Green *et al.* 2010; Gallagher *et al.* 2016). Without geological or soil maps and databases it would be difficult to delineate a possible search area or areas based on the results of analysis alone. As noted above, the use of pollen could also be considered, alongside the earth material analysis, to suggest a possible search area, such as an open meadow, a forest or adjacent to a river (Wiltshire 2015). Some researchers have suggested that the variability of earth materials on a questioned sample, without the use of baseline databases, can only be used in an exclusionary context (Morgan & Bull 2007).

Searches for burials could follow the newly developed and innovative GSS. This developed over a 25 year period during the search for the grave of a murdered child, and associated items, in the north of England (known as the 'Moors Murders' case). The GSS blends conventional geological exploration and engineering geology ground investigation techniques with police and law enforcement strategies and tactics (Donnelly 2003, 2009*a*, 2013, 2017; Donnelly & Harrison 2010, 2013, 2015, 2017, 2020, 2021). One of the fundamental aspects of the GSS is the recommendation for the production of a conceptual geological model to facilitate a search and to help determine the diggability of the ground, the detectability of the target and the suite of search assets most likely to find the desired target. Earth materials recovered from an offender, object or item may support the conceptual geological model in helping to determine a search area or areas (Figs 10 & 11).

The combined role of using earth materials in searches for burials and as trace evidence

Forensic soil science and geology progress not only through the publication of fundamental and applied research, but also through the publication of specific real-life case studies with conclusions admissible in court (e.g. Fitzpatrick *et al.* 2017; Donnelly *et al.* 2019; Fitzpatrick & Raven 2019; Raven *et al.* 2019). Hence, wherever possible, the publication of material in the scientific literature on the success or otherwise of real-life case studies is encouraged to illustrate how forensic examiners studied earth materials and drew conclusions about the meaning

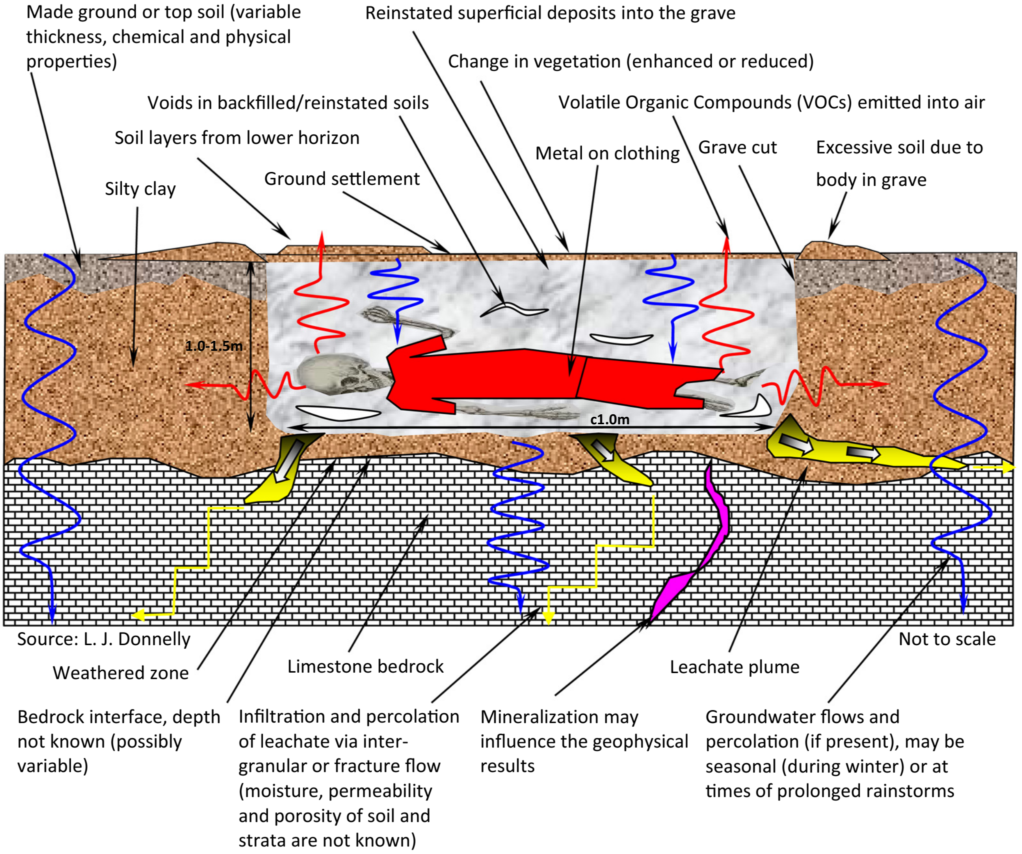

Fig. 10. Conceptual geological model for the grave of a child. Evidential items containing limestone bedrock, mineralization and silty clay soil could verify a search area suspected by law enforcement (source: Laurance Donnelly; UK police search for a missing homicide victim).

of the evidence used to help law enforcement officers solve complex criminal investigations. This is demonstrated here by the real-life case study of a person (victim) who had been missing for 4 months and was last seen by his family at a suburban address in Adelaide, South Australia, in April 2011 (Fitzpatrick *et al.* 2013).

This case illustrates the critical importance of: (1) identifying and characterizing unusual artefacts (e.g. lime) and foreign soil adhering to clothing on a dead body at the crime scene (grave); (2) detailed sampling of natural and artefact earth materials from a range of likely control sites; and (3) detailed X-ray diffraction analyses to identify the presence of unusual minerals (i.e. in this case study at specific locations distant from the crime scene containing calcite and other clay minerals, which had become mixed with the red common soil underlying the entire crime investigation area).

One of the victim's friends confessed in August 2011 to assisting in the murder of the victim at a property on Adelaide's northern outskirts but did not know where the victim was buried. The property with tin sheds and glass houses belonged to the grandparents of another of the victim's friends, who told both the police and the victim's family members that he had witnessed the murder and that the victim's body was probably buried in a shed on the property.

The visual appearance of partly disturbed surface layers of soil and of recently sprinkled small patches of white coloured material, likely to be lime powder (calcite), on the soil surface as shown in Figure 12 assisted police locate a shallow unmarked grave in the corner of a tin shed.

The shallow grave was carefully excavated by forensic police officers as shown in Figure 13. The burial site is in a red clayey soil with various soil layers, rock and calcrete fragments, which underlies the entire crime investigation area. In the adjacent sketch in Figure 13, several distinct patches of white lime are clearly visible in the soil profile, which includes

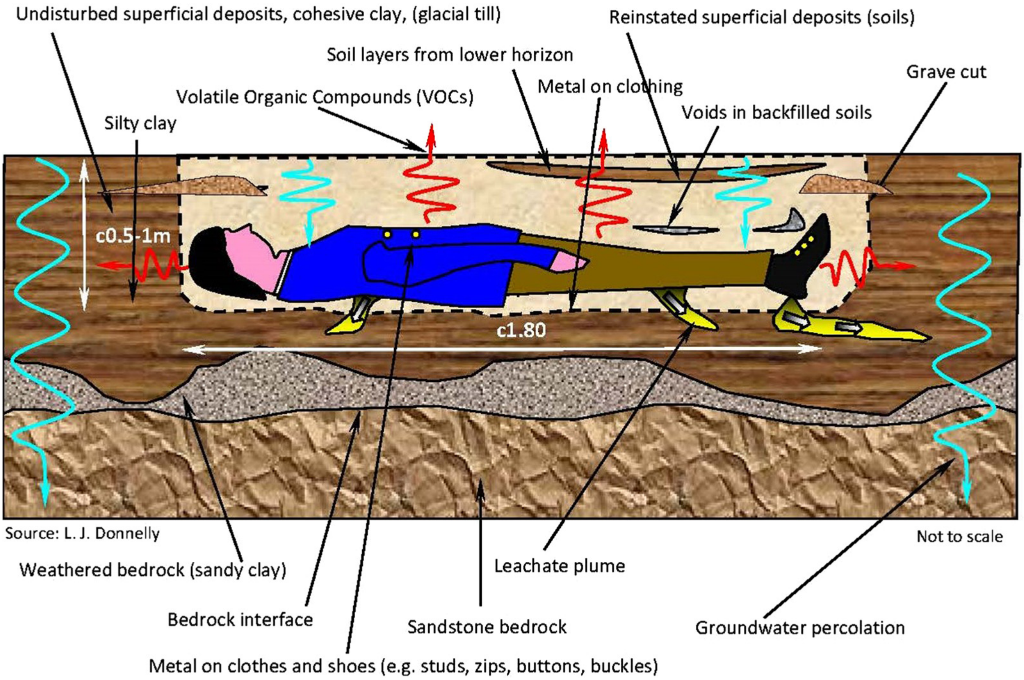

Fig. 11. Conceptual geological model for the grave of an adult. Evidential items containing sandstone bedrock and a cohesive clay glacial till could determine the geological provenance of the materials analysed to delineate a search area, by comparison with geological maps freely available on the internet or mobile phone app, published by the British Geological Survey (source: Laurance Donnelly; UK police search for a missing homicide victim).

Fig. 12. Photograph showing partly disturbed surface layers of soil and recently placed sporadic small patches of white-coloured material likely to be lime powder (calcite) on the soil surface, indicating the likely burial site of a shallow, unmarked, homicide grave in the corner of a tin shed (source: South Australia Police).

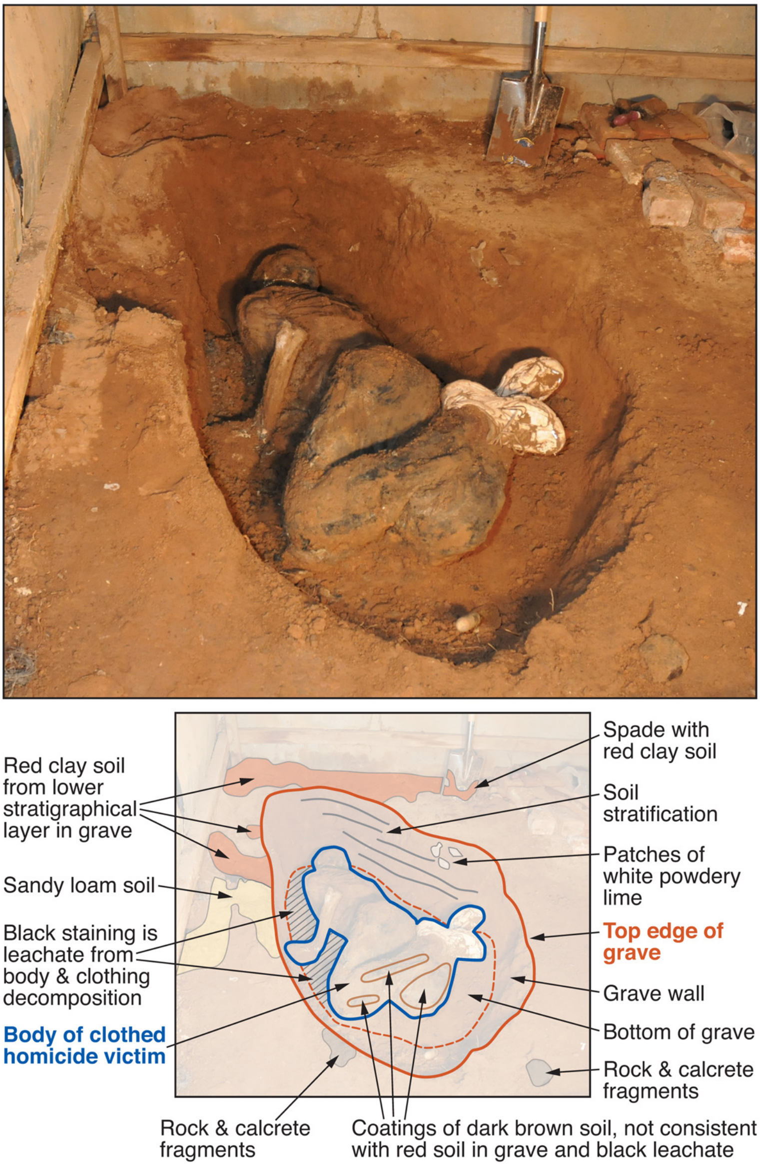

Fig. 13. Photograph of burial site in a red clayey soil with adjacent sketch illustrating: (i) various soil layers, rock and calcrete fragments; (ii) body of clothed homicide victim; (iii) white patches of lime added by accused when the body was placed in the grave; (iv) sporadic coatings of dark brown soil on the victim and in the bottom of the grave from a nearby locality where the body was initially placed; and (v) staining of leachate from body and clothing decomposition (source: South Australia Police).

a torn white plastic bag that protrudes out of the soil profile below the spade and bricks and was probably added by the accused when the body was placed in the grave. In addition, thin irregular coatings of dark brown-coloured soil were found on the deceased's head, face and clothing and at the bottom of the excavated grave. This soil probably originated from a nearby soil locality where the deceased was initially placed before burial in the red soil. The black staining observed surrounding the deceased's body is potentially leachate from body and clothing decomposition. Samples were taken of the dark brown-coloured soil from the deceased's head, face and clothing and patches of white lime (these two samples are referred to as questioned earth materials). For comparison, known control samples were taken of the red clayey soil from within the grave, lime from a 25 kg plastic bag of commercial lime (calcite) located in the adjacent shed and a ‘dark brown-coloured surface soil’ from within a greenhouse located 55 m from the grave site.

Sufficient descriptive and mineralogical (X-ray diffraction analysis) data were acquired on all of the questioned and control earth material samples to determine the major similarities and differences between the samples using ‘Categories of Comparability’ as defined by Fitzpatrick & Raven (2016). It was established that there was a ‘very strong degree of comparability’ of the questioned sample of white lime taken in the grave and the control sample of lime from the 25 kg plastic bag of commercial lime (calcite). This confirmed that the patches of white-coloured material seen in the grave were lime powder (calcite), which was probably added or sprinkled on the deceased’s body prior to burial in the shallow grave (Fitzpatrick *et al.* 2013).

Finally, it was established that there was a ‘moderate strong degree of comparability’ between the questioned dark brown-coloured soil from the deceased’s head/face/clothing and the control dark brown-coloured surface soil sampled from within the distant greenhouse area. The main reason for the slight difference between these two samples is because the head/face/clothing questioned samples have mixed ‘additional’ trace amounts of calcite (lime) and red soil from the grave site containing kaolin, muscovite and hematite. A likely explanation for this is that the calcite (lime) originated from commercial lime being added or sprinkled on the deceased’s body prior to burial in the shallow grave, in a failed attempt by the offender to reduce decomposition and odour from the grave to mask its presence. The origin of the small amount of ‘smectite/vermiculite’ in samples from the deceased’s head/face/clothing is probably either of the following two scenarios:

- The deceased’s body was first placed in or on soil at another nearby locality in the greenhouse that contained high amounts of ‘smectite/vermiculite’, which in turn was transferred to the exposed skin on the deceased’s head/face and clothes.
- A soil containing a high amount of ‘smectite/vermiculite’ was transported from a nearby locality and placed or sprinkled on the deceased’s head/face and clothes in the open shallow grave, perhaps together with lime.

The prominent black staining, which is clearly observed in the middle of the excavated grave after removal of the body of the clothed homicide victim, is possibly leachate from the body and clothing decomposition as shown in Figure 14. It has been suggested that leachate and volatile organic compounds (VOCs) may potentially be used to detect the presence of a shallow, unmarked, homicide grave (Donnelly & Harrison 2013, 2015, 2020,

Fig. 14. Photograph of burial site after removal of the body of a murdered clothed man showing: (i) staining of leachate from body and clothing decomposition; (ii) white patches of lime added by accused when the body was placed in the grave; and (iii) sporadic coatings of dark brown soil in the bottom of the grave from a nearby locality where the body was initially placed (source: South Australia Police).

2021; Donnelly *et al.* 2021, chapter 5). Furthermore, the white patches of lime added by the accused when the body was placed in the grave and sporadic coatings of dark brown soil in the bottom of the grave from a nearby locality where the body was initially placed were clearly observed in the grave after removal of the body (Fig. 14). The presence of the white lime actually drew attention to the grave, as this was conspicuous against otherwise reddish-brown soils.

In summary, given the mineralogical and morphological similarities between the questioned lime sample collected in the grave and the control samples of lime from the 25 kg plastic bag of commercial lime, it is likely that the questioned lime sample came from lime powder used by the farmer to coat the glass in the glass houses. The questioned soil samples recovered from the head/face/clothing of the deceased are a mixture of soil and lime materials, comprising:

- Natural red soil (dominant), which is likely to have originated from the grave site in the tin shed.
- Lime (minor), which is likely to have originated from commercial lime powder, which was used by the farmer to coat/paint the glass on the glasshouses.
- Natural dark brown-coloured soil (minor/trace), which is likely to have originated from a soil type with a high amount of smectite/vermiculite, somewhat distant from where the deceased's body was buried.

Observation and analyses of several kinds of earth materials assisted the police to find the buried body and were also used as trace evidence in cooperation with law enforcement to successfully help solve a complex homicide investigation, being presented as evidence during a trial before a jury. The victim's friend was jailed for at least 22 years for luring the victim to the property of his grandparents and then bludgeoning him to death with a hammer before dining with the victim's family. Two other men were jailed for more than 10 years after admitting their part in the killing.

Overview of papers in this special publication

There are 20 papers published in this Special Publication on forensic soil science and forensic geology. These provide insight for the reader into the broad range of forensic studies relating to earth materials, forensic soil science and forensic geology currently being undertaken globally. The various global locations of operational case studies, research and investigations and other examples used in this Special Publication are shown in Figure 15.

This Special Publication is organized into four sections. The first is an introductory section, including this paper focusing on background and importance of forensic soil science and forensic geology. Second, there is a section on the design, implementation and management of ground search for burials (seven papers), comprising crime scene searches that have been conducted in Europe (England, Northern Ireland and Italy) and South America (Colombia, Venezuela and Brazil). Third is a section based on the trace evidence (five papers) with operational case studies comprising samples that were collected from earth materials in Europe (The Netherlands), South America (Colombia, Venezuela and Brazil), Asia (China and South Korea), Australia (Western Australia and South Australia) and Africa (South Africa). The fourth section discusses recent research and developments (five papers), including studies involving earth materials from Europe (Italy, Scotland and England), the USA and Australia.

Background and importance

Two papers in this volume illuminate the background, importance and role of different earth materials and landscapes in searches for burials. This introductory paper by (1) **Fitzpatrick & Donnelly** in some ways represents a review of our current understanding and historical overview of the use of earth materials in searches for burials and as trace evidence to help police and law enforcement in solving criminal, environmental and terrorism investigations.

(2) **Kobus & Robertson (2019)** review and discuss the importance of forensic soil science and forensic geology being connected to mainstream forensic science. Despite a resurgence in earth material examination associated with criminal investigations, they believe that its full potential has probably not been realized. However, they caution the reader that the necessity to have a strong interface between specialist services involving earth material examination and mainstream forensic science needs to be carefully managed to ensure the best outcome. The authors compare DNA evidence, which is held up as the 'gold standard' owing to its ability to provide numerical probabilistic interpretation, with the limitations or inability of earth material examination to provide quantitative probabilistic interpretations. As such, they emphasize the importance of forensic soil scientists and forensic geologists involved in forensic science being aware of the interpretation issues impacting on the forensic sciences, but also being aware of contemporary approaches to interpreting and evaluating data for forensic application. To avoid these potential pitfalls and problems that forensic soil science and geology specialists operating in the legal environment may face, the authors

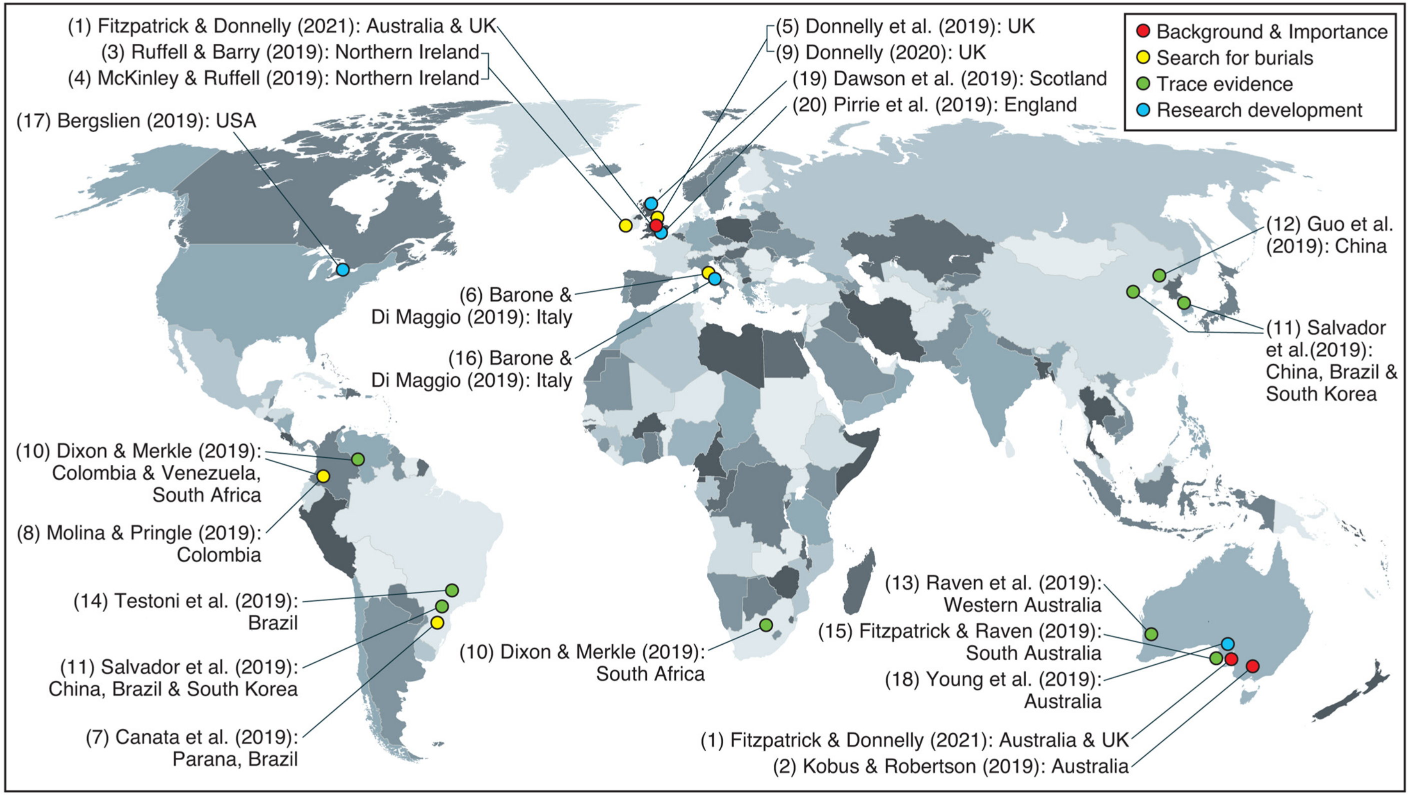

Fig. 15. The global distribution and locations of research, investigations or police and law enforcement operations case presented in papers of this Special Publications. Each associated paper is indicated by numbers 1–20 in order of appearance. Each paper is also indicated by marker colours: red, background and importance; yellow, ground searches for burials; green, trace evidence; and blue, research and developments. The co-authors for each paper presented were: (1) Fitzpatrick & Donnelly (this paper), Australia and England; (2) Kobus & Robertson (2019), Australia; (3) Ruffell & Barry (2019), Northern Ireland; (4) McKinley & Ruffell (2019), Northern Ireland; (5) Donnelly *et al.* (2019), England; (6) Barone & Di Maggio (2019), Italy; (7) Canata *et al.* (2019), Brazil; (8) Molina & Pringle (2019), Colombia; (9) Donnelly (2020), England; (10) Dixon & Merkle (2019), Colombia, Venezuela and South Africa; (11) Salvador *et al.* (2019), China, Brazil and South Korea; (12) Guo *et al.* (2019), China; (13) Raven *et al.* (2019), Australia; (14) Testoni *et al.* (2019), Brazil; (15) Fitzpatrick & Raven (2019), Australia; (16) Di Maggio & Barone (2019), Italy; (17) Bergslien (2019), USA; (18) Young *et al.* (2019), Australia; (19) Dawson *et al.* (2019), Scotland and (20) Pirrie *et al.* (2019), England.

identify the following guidance issues: (1) specialists should stay strictly within their realm of expertise; (2) specialists must follow accepted analytical protocols; and (3) specialists should have the ability to provide an interpretation of the results and be able to provide a weight to the evidence that can be scientifically justified. The authors emphasize that the key element to ensure the best outcomes for earth materials as an evidence category is for strong partnerships to be established between specialist soil science and geology organizations and operational forensic science laboratories.

Search for burials

There are seven papers that focus on or include searches for burials from Northern Ireland, England, Italy, Brazil and Colombia (Fig. 15). Collectively, these provide informative and practicable guidance on different aspects of search. A particular value of this section lies in the operational case studies provided. Often, obtaining permission to publish case work can be challenging and time consuming, owing to its high profile nature and sensitive information or if it is an ongoing case. Most of the cases presented have been anonymized.

(3) **Ruffell & Barry (2019)** emphasize the importance of a desk study in the initial stages of a search, as advocated by the GSS initiated by Donnelly (2002*a*, *b*, 2003) and developed by Donnelly & Harrison (2013, 2015, 2020, 2021). Performing a desk study before a search begins is important to identify, collate and evaluate geological data and information and police or law enforcement evidence and intelligence. Desk studies identify gaps in knowledge and enable the resources to become focused on gathering data and information of importance and material relevance for the search. Two case studies are presented in this paper. In the first, an investigation included geophysical surveys conducted to determine the ground conditions ahead of construction. This was preceded by a desk study including the collation and analysis of past topographical maps published by the Ordnance Survey. These showed the site to be adjacent to a Jewish cemetery and therefore the presence of human remains could be anticipated. In the second case, the results of the desk study and analysis of past topographic maps showed the site under investigation to have formerly been an industrial works. This was infilled with sand, which had a significant influence on the drainage, resulting in flooding. The results of the desk study were shown to be crucial in permitting the correct interpretation of the geophysical data in context with past land use.

(4) **McKinley & Ruffell (2019)** provide a paper on GIS and demonstrate the value of using GIS as part of a search for a missing person. By using GIS it is possible integrate and analyse georeferenced data. This may be undertaken in the desk study and when data becomes available during the search. The paper also demonstrates how geological trace evidence, recovered from the footwell of a vehicle, was used to assist in the identification of a search area, as advocated in the GSS (Donnelly & Harrison 2021). The GIS was able to efficiently and cost-effectively integrate various datasets including soil databases and regional geological data to suggest the geographical provenance of the sand for control (or alibi) samples. Subsequently, 77 soils were collected and analysed from the suspected crime scene. The results of the GIS demonstrated that fewer soil samples would have been required to associate the questioned items with the crime scene, but would not have demonstrated how other areas could be progressively excluded from the comparison. Two suspects were convicted of involuntary manslaughter.

(5) **Donnelly *et al.* (2019)** provides the results of soil analysis following the search for a homicide grave and the recovery of the victim who had been missing for 15 years. New intelligence provided a search area in a remote, upland location. A preliminary search was conducted and the police detector dogs showed interest in one particular location, but subsequent excavations did not locate the grave. During the initial part of the search false-positive detector dog indications were explained as representing the emergence of a leachate plume and VOCs flowing from the victim's remains that had undergone partial decomposition in organic, peat-rich soils. Leachate plumes were observed flowing from human remains found at crime scenes by the Human Decomposition Research Facility (The Body Farm), located at the University of Tennessee, Department of Forensic Anthropology, at Knoxville, Tennessee, USA. Police in England had received information that a person was missing. A search was conducted but the person or body was not found.

The GSS was initiated on Saddleworth Moor in northern England in 1994 as part of the search for the last remaining victim of the 'Moors Murders' (Donnelly 2002*a*, *b*, 2003) and refined with the police and law enforcement in the 25 years that followed (Donnelly & Harrison 2013, 2015, 2020, 2021). The GSS was applied for this particular search and the grave of the victim was found at a depth of less than 1 m and forensically recovered. With permission from the police, this provided the opportunity for soil samples to be taken from beneath the grave, upslope, downslope and along strike. The results of the analysis of the soil samples, in comparison with a control sample, indicated the presence of leachate flowing from the grave, showing elevated putrescine and stanols. Furthermore, there was a change in the mineralogy of the soil by the growth of *in situ* calcite crystals in the soil immediately below the grave. This strategy may potentially be used to reduce a search area or verify the presence of a human decomposition event if leachate (or volatile organic compounds) can be detected in the soil.

(6) **Barone & Di Maggio (2019)** discuss the management of different targets from crime scenes in Italy that must be properly managed and coordinated by investigating officers and other forensic scientists, ensuring that all materials investigated and recovered follow forensic best practice. The first case involves a child who had gone missing 25 years earlier, with the case being reopened by the Italian Carabinieri. The second case concerns the illegal tipping of waste, including asbestos, in relative close proximity to the sea in Sicily. In both cases, the Carabinieri received new intelligence that resulted in the investigations being reopened. A third case focusses on antiquities crimes along the Italian Adriatic coast, where a high-profile archaeological find had been reported. Geophysical surveys were used to determine the extent of the archaeological site to control development and/or building. This paper demonstrates the value of forensic soil science and forensic geology and their broad applications in criminal, environmental and cultural investigations.

(7) **Canata *et al.* (2019)** provides information on a geophysical survey, using ground penetrating radar (GPR), conducted at an archaeological site in Brazil. The Brazilian Federal Constitution does not permit crimes against sites of cultural heritage. When such crimes occur, these become the responsibility of the Brazilian Federal Police to investigate. This particular archaeological site is located in the state of Paraná, between two cities, Terra Roxa and Guaíra, and is understood by archaeologists to be related to the Tupi–Guarani traditions. A breach of this archaeological site was reported to the Brazilian Federal Public Prosecutors Office during the construction of a port. This case was subsequently investigated by the Technical-Scientific Section of the Brazilian Federal Police, working in collaboration with universities. The Tekoha Jevy indigenous village was the site chosen to deploy the geophysical investigation. This comprised acquiring GPR data along 32 traverses using the 250 and 700 MHz shielded antennas. The GPR anomalies were invasively verified by excavation, which detected the presence of ceramic artefacts on the banks of the River Paraná, associated with ancient indigenous people. Those responsible for damaging the site of archaeological and cultural heritage are subject to prosecution.

(8) **Molina & Pringle (2019)** compare geophysical and botanical results in simulated clandestine graves in rural and tropical environments in Colombia, South America. Many of the countries in South America have a significant number of missing persons who have 'disappeared' as a result of the actions of political regimes or criminal cartels. In Colombia alone, there are an estimated 84 000 missing persons. Searches for graves covering vast areas, often covered with thick, lateritic soils and jungle, can be challenging. This paper provides the results of geophysical surveys conducted on simulated graves, which were imaged to identify over time any characteristic geophysical signatures and/or changes in vegetation that could the potentially be applied to actual searches. Twelve simulated graves were excavated in two different locations, at depths of 0.5 0.8 and 1.2 m, and monitored over two years. The targets in the graves were three pig carcasses, three human skeletons, three graves containing burned human and beheaded skeletons and three graves with no contents. The geophysical methods used were GPR, magnetic susceptibility, ground conductivity and electrical resistivity, which gave good success in tropical rainforests. Also observed was the enhanced growth of vegetation, including *Raphanus* in the tropical rainforest and *Petiveria* at the rural site.

(9) **Donnelly (2020)** presents a SOP for earth material sampling for the detection of VOCs and leachate associated with human decomposition from a shallow, unmarked, homicide grave as outlined in **Donnelly *et al.* (2019)** (Chapter 5). The homicide case from England presented by **Donnelly *et al.* (2019)** is an excellent example of the application of the GSS. Here, a search was planned based on a detailed evaluation of the geology and case intelligence. This resulted in the recovery of a homicide victim who had been buried 15 years earlier. Following the recovery of the victim, soil samples were taken from beneath, downslope and adjacent to the grave. The results supported the hypotheses for the generation of leachate plumes in the vicinity of a homicide grave, which may be of use for open area searches in similar geological settings. This assumes that the VOC and leachate generated by a human decomposition event are detectable in the soil. The SOP, which was initially developed on Saddleworth Moor, northern England, during the search for the last remaining Moors Murder victim, subsequently developed and evolved. This SOP provides a framework and suggested procedure for collecting soil samples for leachate and VOC analysis. This SOP has already been used on several high-profile searches for missing persons and could potentially be used by forensic geologists, police and law enforcement during open area searches, across large tracts of land, to detect potential human decomposition products in soils, to reduce a search area or to verify the existence of a homicide grave. It should be noted that this technique remains somewhat experimental. Further research is recommended at

homicide grave sites and at human decomposition facilities that are now operational in different parts of the world (e.g. USA, Canada, Europe and Australia), where the geology and environmental conditions will vary. The technique could potentially be used as a supportive method in police searches, but not a lead search method until it has been further refined and validated.

Trace evidence

The six papers in this section offer valuable insight into recent research and applications on trace evidence from samples in Colombia, Venezuela, South Africa, China, Brazil, South Korea, Western Australia and South Australia (Fig. 15).

(10) **Dixon & Merkle (2019)** investigated and identified the source of illicit gold from South America, which is increasingly becoming a serious global problem. They specifically used trace element profiling of gold as a technique aimed at the determination and quantification of minor and trace components, which allows a unique characterization of materials from ores to flotation concentrates, smelter products and materials at different steps in the refining process, and finally the commercially available products. Gold bars were submitted for analysis, with a request to determine whether the likely origin of the gold was the Chocó region in Colombia or the Bolivar State in Venezuela. The authors' results indicated that gold from different deposits can be distinguished on the basis of its trace element distribution, even if it has been processed and thus is not in its original form when analysed. However, this discrimination is very dependent on a good knowledge and understanding of the various genetic processes that act at the origin of the ore deposit, as well as the processes employed in extracting the gold into its first transportable and tradeable form. This paper has contributed to the increasing emphasis on tracing gold through the global supply chain to ensure that it does not come from an illicit source, which has major ramifications for gold refining companies around the world. For example, this requires not only a certification process but also a physical record of gold samples against which the origin of a shipment may be confirmed.

(11) **Salvador *et al.* (2019)** investigated and identified the source of finely crushed rock, that was used as 'substitution material' for zinc ingots acquired by a Brazilian company from a Chinese supplier in a major investigation of fraud and theft. The zinc ingots were substituted at some point during their journey, and replaced with bags containing fine crushed rock as a substitution material. The authors conducted mineralogical (X-ray diffraction), scanning electron microscopy coupled with an energy dispersive X-ray analysis, petrological isotope analysis (carbon and oxygen isotopes) and micropalaeontology (Cnidarian microtraces) to confirm that the replaced crushed rock did not originate from a Brazilian provenance. Therefore, the substitution possibly occurred before the cargo's arrival in Brazil. The authors concluded that it was possible to demonstrate that the substituted zinc ingots probably originated from Asia and not South America, therefore excluding the Paranaguá region as the source. Moreover, they confirmed that the isotopic signals were compatible with other investigations indicating that the replaced crushed rock probably originated from South Korea.

(12) **Guo *et al.* (2019)** investigated a homicide in the Jilin Province, in the NE of China, where a dead body was found with soil adhering to the clothing (questioned soil). Based on the soil morphology characteristics (soil colour and texture) of the questioned soil it was found to be different from the control soil located where the body was found. The authors concluded that the body was likely to have been transferred from another location based mainly on DNA barcoding evidence on species of plant debris (roots) located in the questioned soil sample, which probably originated from ginseng plants. This critical information indicated that the questioned soil probably originated from a ginseng plantation, suggesting the place where the body was initially buried. The authors used mineralogy (X-ray diffraction), geochemistry and pollen analyses to compare the control soil samples taken from where the body was located and from the ginseng plantation. These soil forensic examination results confirmed that the questioned soil sample was identical to the control soil samples taken from the ginseng plantation. Trace amounts of soil located on the body played an important role in locating the burial site and were regarded as the most valuable evidence in convicting the suspect of murder even without the suspect's DNA being available.

(13) **Raven *et al.* (2019)** provided detailed trace evidence using laboratory and synchrotron X-ray diffraction techniques in a 2007 homicide in Western Australia involving small (0.5 mm diameter) red brick fragments and soil on the victim's clothing (mainly bra), body (mainly hair) and vehicle. The authors conducted a comparative study of the mineralogy and morphology of the red brick fragments with red bricks from the paved area in front of the victim's house using traditional laboratory X-ray diffraction (XRD) on low-background silicon wafer holders and a 0.5 mm focusing monocapillary attachment. While their data indicated significant similarities between the two datasets, peak overlaps and poor resolution prevented a specific provenance to be determined. Consequently, the authors conducted a series of additional analyses using the superior intensity and resolution of synchrotron XRD at

the Australian Synchrotron, which quantified the mineralogy of polycrystalline minerals (cristobalite and mullite) in the small brick fragments. These data established that the brick fragments could not be distinguished from the driveway bricks and were clearly shown to be different from a range of other possible sources. The authors presented this evidence during a trial before a judge only and concluded that the mineralogy data from the small brick fragments on the victim's clothing and the bricks from the victim's front driveway indicated that she was initially attacked in her front yard and not at the distant locality (i.e. Kings Park) where her body was buried.

(14) **Testoni *et al.* (2019)** provide an evaluation of 'sequential physical, chemical and mineralogical analyses' of soil samples from a previous real crime that occurred in the Curitiba Metropolitan Region of Brazil, which included forensic soil traces from a crime scene involving a robbery of a safety deposit box in Brazil. The authors conducted sequential physical, chemical and mineralogical analyses on the soil samples. Multivariate analysis (principal component analysis) was used to verify the relative positioning of soil traces, which had been previously recovered from a stolen safety deposit box (SDB) in a vehicle suspected of being used in its transportation and from the site allegedly used in the opening of the SDB. The authors indicated that the methods employed were effective in discriminating between the sampling sites. The soil from the site used in the opening of the SDB could be excluded as being the location where the soil transferred to the SDB had originated as it was different in many characteristics.

(15) **Fitzpatrick & Raven (2019)** undertook a multidisciplinary approach to compare trace amounts of questioned soil on a victim's pyjama top, comprising hypersulfidic subaqueous soil from a river in an estuary to provide evidence in a homicide cold case. The paper included detailed soil morphological descriptions of questioned and control soil samples in police archives and the use of existing soil maps and associated pedological data to assist in classifying the soil samples (i.e. subaqueous acid sulfate soils). This critical pedological information was used to select soil samples for detailed micromorphology analyses, using scanning electron microscopy as well as standard XRD and synchrotron µ-XRD to identify similarities between soil and clay assemblages on a pyjama top and hypersulfidic subaqueous soils containing pyrite in the Onkaparinga River estuary. The paper also included a series of critical 'soil transference shaking experiments' to determine how small particles of soil became impregnated in the gaps between fibres of the fabric on the victim's pyjama top. This involved 'shaking swatches of the victim's pyjama top with various types of soil samples in water'. In essence, the combined pedological data and mineralogical analyses data were used to construct a 'soil genesis model' to confirm that the mineral particles were deeply impregnated in the gaps between the fibres of the fabric, which probably occurred under water with force being applied on the pyjama top, implying that the victim was pushed into mud comprising subaqueous soils containing pyrite. In addition, an understanding of basic soil processes indicated that, because salt (namely halite) was not identified on the victim's pyjama top, it is likely that the pyjama top was subsequently leached via rain events or washed in freshwater to remove water-soluble salts. The accused was found guilty by a Supreme Court judge of murder.

Research developments

The final section of this volume contains five papers that might loosely be grouped under the heading of Research Developments. The papers in this section continue the effort to illuminate the roles of different earth materials as trace evidence (Fig. 15).

(16) **Di Maggio & Barone (2019)** provide a critical evaluation of forensic geoscience or geoforensics in Italy. The authors specify that forensic geoscience not yet as popular as other forensic sciences, such as forensic genetics, bloodstain pattern analysis, ballistics and fingerprints. They also highlight the lack of undergraduate and graduate teaching programmes in forensic geoscience in Italy. A possible explanation for the lack of interest in using earth materials to assist in solving crimes in Italy can be ascribed to the perceived 'risk of elevated uncertainties related to some of the methods applied'. According to the authors, forensic investigations in Italy have no geoforensic or standard protocols to provide the country's law enforcement agencies with the materials to create a multidisciplinary approach to crime scene investigation, using the correct personnel and appropriate tools. The authors ascribe this situation in Italy to several factors, but indicated that the main two are: (1) a lack of education, which allows the so-called 'CSI effect' to spread at all levels of society; and (2) a lack of proper financial and environmental resources to support research. Moreover, the stressful context and psychological pressure of working with law enforcement agencies impedes the creation and implementation of proper protocols and standard procedures to the level attained in other better known forensic sciences. The authors conclude that a possible solution to this 'vicious circle' can be investment in education, especially by training geoscience specialists to: (1) explain forensic geoscience technical matters and protocols in easily comprehensible terms and (2)

improve their skills in working more closely with law enforcement agencies.

(17) **Bergslien (2019)** highlights some of the areas of main concern during forensic analyses of earth materials by practitioners using portable X-ray fluorescence (PXRF) spectrometry. The author shows that miniaturization of components and other advances in technology have resulted in significantly increased availability of PXRF units, leading to a boom in their use in a variety of fields. An unfortunate corollary, according the author, is that there has also been a boom in the publication of data of doubtful quality, based on misunderstandings of PXRF and the underlying physics of X-ray fluorescence. The author provided a caution that many manufacturers sell the units as 'point-and-shoot black boxes, capable of generating usable data under a range of conditions but, in reality, all of the assumptions and limitations inherent in laboratory-based XRF systems still apply or are even amplified in portable units'.

(18) **Young *et al.* (2019)** provide a broad comprehensive overview of forensic DNA analyses and describe the differences between DNA analysis of a single specimen and complex soil–DNA mixtures. The organic component of soil includes a vast number of living organisms, and the combination of these organisms can provide a biological signature to assist with soil comparisons. The authors highlight the recent developments in DNA sequencing technology, which enable the characterization and comparison of these complex soil communities. DNA analysis is routinely applied in forensic science to answer human- and non-human-related questions. However, despite initial studies demonstrating the potential of soil DNA analysis to assist forensic investigations, the authors emphasize that further research is required to explore the use of indicator taxa for identifying the likely origin of an unknown soil to evaluate the strength of a soil comparison using large reference databases and, ultimately, to integrate this analysis into routine casework. However, before this approach can be employed as an additional tool in actual forensic soil science cases, additional studies are required to assess and quantify the vast variation in 'soil community' in different locations and habitats, and especially in soils that are subjected to seasonal variations (e.g. wetting and drying of acid sulfate soils).

(19) **Dawson *et al.* (2019)** investigated the use of biochemical (*n*-alkane and fatty-alcohol plant wax compounds) and biological (bacterial and fungal community DNA profile) biomarkers to provide investigative information both as intelligence and as evidence. The authors selected two contrasting urban areas in Scotland (Aberdeen) and the south of England (Milton Keynes) based on distinct underlying geology, but with similar land-use and vegetation types to test the analysis methods. Their results demonstrate the limited potential of basic soil physicochemical analysis, mineralogy (X-ray diffraction) and spectroscopic (colour and Fourier transform infrared) methods in providing land-use intelligence within these specific localized urban environments. Their results also demonstrated the complementary nature of biochemical/biological analysis to mineralogy, providing important information about the variability of analysis in localized urban environments. The *n*-alkane compounds proved variable within land-use types. The bacterial DNA profiles were influenced by both land use and the urban/geographical origin. Fatty alcohol compounds and fungal DNA profiles provided characteristic analyses that discriminated grass-dominated, flowerbed, woodland and roadside soils, regardless of urban/geographic origin.

(20) **Pirrie *et al.* (2019)** present a comprehensive systematic study of the relationship between the underlying geology and soil mineralogy in a geologically varied 3500 km^2 area of SW England. The authors applied automated mineralogical profiling of soils as an indicator of local bedrock lithology to provide a tool for predictive forensic geolocation (i.e. to use soil evidence to identify an unknown location). The use of soil evidence to identify an unknown location relies on understanding and predicting how soils vary in composition depending on their geological/geographical setting. The authors established compositional links between the mineralogy of 40 soils and the underlying bedrock geology, as documented in local-scale geological maps. The mineralogy of the soils was quantified using automated scanning electron microscopy–energy dispersive X-ray spectrometry analysis based on QEMSCAN technology. Soil mineralogy and texture as measured using this technique were found to be consistent with the underlying geology as indicated by regional-scale geological mapping. Furthermore, the authors identified differences between individual units of the same bedrock lithology, such as different granites, by examining trace mineralogical signatures. From an investigative viewpoint, the authors demonstrated that rapid automated mineral profiling of soil samples could be used, in conjunction with readily available geological mapping or similar datasets, to provide an indication of the areas from which a soil sample of unknown origin could, or could not, have been sourced.

Summary, outlook and perspectives for the future

This Special Publication provides a representative snapshot of the exciting state of the use and applications of earth materials in forensic science and firmly establishes forensic soil science and forensic geology as flourishing subdisciplines of soil science and geology that merit the broadest exposure across the academic and corporate geosciences, the police and law enforcement. Forensic soil science and forensic geology comprise an all-encompassing subdiscipline that borrows heavily the approaches and techniques of a broad variety of specialist fields including pedology, mineralogy, geophysics, mineral exploration, engineering geology and mathematics, to name but a few, and delivers new insights based on the investigation of real-life, operational police and law enforcement case studies from around the world. Forensic soil science and forensic geology are rapidly evolving, being driven in part by the global success of the IUGS-IFG. The IUGS-IFG has brought together forensic soil scientists, forensic geologists, police and law enforcement to advance and promote the use of earth materials in the investigation of crime from throughout the world. This Special Publication has provided an indication of the wealth of activity, advancements and innovation and a glimpse into the state of forensic soil science and forensic geology in the second decade of the 2000s.

This Special Publication is intentionally ambitious in its scope and diversity. It has pulled together a wide range of contributions from across the disciplines and drawn upon the experiences of forensic soil scientists and forensic geologists involved in the search for burials and the provision of trace evidence. Until the development of organizations such as IUGS-IFG, these fields were normally, conventionally, addressed in single, separate, publications. The reader can select from 20 papers the parts of most interest and absorb related issues for closely related fields and the cross-fertilization of ideas, techniques and strategies. For example, an emerging area for more detailed soil comparison is DNA analysis as emphasized by **Kobus & Robertson (2019)**. Two approaches have been used as described by Khodakova *et al.* (2014) and **Young *et al.* (2019)**. However, Khodakova *et al.* (2014) targets the total DNA in soil and **Young *et al.* (2019)** characterizes species-specific DNA such as that from fungi and plant materials (e.g. **Guo *et al.* 2019**). In both approaches, immense parallel sequencing techniques are used and the analytical data requires relatively complex bioinformatics analysis. The determination of quantitative probabilistic interpretations as occurs with human DNA is not possible in soils. While the current two approaches provide a potential powerful exclusionary technique, clearly more work needs to be done on soil DNA to fully understand it is potential for routine use in soil forensic investigations.

An overview has been provided in the volume of the wide range of operational case studies undertaken to elucidate the complex and important role that soil science and forensic geology play in using earth materials to help the police and law enforcement investigate and solve crimes. Future studies on these topics will help to further refine and quantify the details of the role of earth materials in forensic science and forensic geology. However, for forensic soil science and geology to remain sustainable into the future this will require as a minimum the following, which is largely in agreement with the sentiments expressed by **Di Maggio & Barone (2019)** and Donnelly (2018):

- Investments are needed in forensic soil science and forensic geology teaching and research.
- Formal training, learning and development are required.
- Regulation and accreditation of practising forensic soil scientists and forensic geologists are necessary.
- The current level of forensic soil science and geology training for practitioners, lawyers and the judiciary does not formally exist. Although, by invitation, members of IUGS-IFG have regularly engaged with law enforcement agencies and the military across the world to provide training in forensic soil science and forensic geology.
- Forensic soil scientists and forensic geologists in most countries (e.g. apart from China, Brazil, Columbia and Russia) are not employed by the police or private forensic consultancies. As such, other forensic specialists conduct work that should be undertaken by a forensic soil scientist or forensic geologist.
- The next generation of forensic soil scientists and geologists needs to be encouraged. As experienced forensic geologists retire, there is some evidence across the world (e.g. UK, Australia, Japan, Italy and USA) that the next generation is not entering this profession. There is enormous interest in forensic science from schoolchildren and university students (e.g. Pirrie *et al.* 2013*a*, *b*). However, there seems to be relatively little support to enter the profession. Furthermore, there is a perception that there are no or only a few opportunities, and that these are not too well paid. This could potentially negatively influence the sustainability of forensic soil science and geology. What is more, geologists and soil scientists require training in some aspects of policing and the judicial system. This could be introduced at BSc level. Ideally, the national school curriculum could include an introduction to forensic soil science, including forensic geology, to maintain and develop the enthusiasm and huge interest amongst schoolchildren and university students.

In recent years, forensic soil science and forensic geology have been applied to crimes that have taken place in the minerals, mining and metals industries. Civilization could not exist as we know it without the minerals upon which it relies. However, there is a growing global crime problem. According to intelligence and information obtained by IUGS-IFG, this includes, but is not restricted to: (1) illegal mining beyond regulatory control; (2) fraud; (3) theft; (4) adulteration of mineral concentrates or processed metals; (5) the substitution of samples ahead of assaying; (6) the mining and trading of conflict minerals; (7) mineral smuggling; and (8) fakery. The IUGS has commissioned the IFG to undertake a ‘Special Project’ that aims to: (1) evaluate the current global scale of mining-associated crimes and (2) assess geological methodologies that may aid law enforcement agencies in the detection, prevention, management and mitigation of mining crime and the identification of the necessary research priorities to develop rigorous protocols to aid law enforcement and the global minerals supply chain. The scope includes: (1) precious metals, base metals and minor metals (including fraud, i.e. substitution, adulteration and theft); (2) conflict minerals; (3) battery minerals; (4) diamonds and gemstones (including fakes and fraud); (5) fossils (including fakes and fraud); (6) criminal networks, cartels and law enforcement; and (7) environmental and social aspects.

Forensic soil science and forensic geology are increasingly transdisciplinary, requiring researchers from many different scientific backgrounds to work together to answer many common questions in this rapidly developing field. These may provide the basis for the development of agreed standards, protocols and SOPs.

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References

Bailey, H.W., Gallagher, L.T., Moncrieff, A. & Wood, C.J. 2017. Calcareous micropalaeontology in forensic investigations with particular reference to the so-called ‘Soham murder case’. *In*: Williams, M., Hill, T., Boomer, I. & Wilkinson, I.P. (eds) *The Archaeological and Forensic Applications of Microfossils: A Deeper Understanding of Human History*. The Micropalaeontological Society, Special Publications, 279–289.

Barone, P.M. & Di Maggio, R.M. 2019. Dealing with different forensic targets: geoscientists at crime scenes. *In*: Fitzpatrick, R.W. & Donnelly, L.J. (eds) *Forensic Soil Science and Geology*. Geological Society, London, Special Publications, **492**, https://doi.org/10.1144/SP492-2017-274

Bergslien, E.T. 2019. Portable X-ray fluorescence (PXRF) spectrometry of earth materials: considerations for forensic analysis. *In*: Fitzpatrick, R.W. & Donnelly, L.J. (eds) *Forensic Soil Science and Geology*. Geological Society, London, Special Publications, **492**, https://doi.org/10.1144/SP492-2017-346

Blume, H.-P., Bolter, M. & Kusber, W.-H. 2012. Christian G. Ehrenberg and the birth of soil microbiology in the middle of the 19th century. *Journal of Plant Nutrition and Soil Science*, **175**, https://doi.org/10.1002/jpln.201100253

Bobrowsky, P.T. & Marker, B. (eds) 2018*a*. *Encyclopaedia of Engineering Geology*. Sedimentary rocks. Springer, Berlin, 710–711.

Bobrowsky, P.T. & Marker, B. (eds) 2018*b*. *Encyclopaedia of Engineering Geology*. Igneous rocks. Springer, Berlin, 506–507.

Bobrowsky, P.T. & Marker, B. (eds) 2018*c*. *Encyclopaedia of Engineering Geology*. Metamorphic Rocks. Springer, Berlin, 711–712.

Canata, R.E., Salvador, F.A.S., Borges, W.R., Ferreira, F.J.F., Seimetz, E.X., Pinto, I. & Barros, E.O. 2019. The forensic application of ground-penetrating radar, Tekoha Jevy indigenous village, Paraná, Brazil. *In*: Fitzpatrick, R.W. & Donnelly, L.J. (eds) *Forensic Soil Science and Geology*. Geological Society, London, Special Publications, **492**, https://doi.org/10.1144/SP492-2017-329

Dawson, L.A., Macdonald, L.M. & Ritz, K. 2019. Plant wax compounds and soil microbial DNA profiles to ascertain urban land use type. *In*: Fitzpatrick, R.W. & Donnelly, L.J. (eds) *Forensic Soil Science and Geology*. Geological Society, London, Special Publications, **492**, https://doi.org/10.1144/SP492-2018-65

Di Maggio, R.M. & Barone, P.M. 2019. Geoforensics in Italy: education and research standards. *In*: Fitzpatrick, R.W. & Donnelly, L.J. (eds) *Forensic Soil Science and Geology*. Geological Society, London, Special Publications, **492**, https://doi.org/10.1144/SP492-2017-273

Dixon, R.D. & Merkle, R.K.W. 2019. Identifying the source of illicit gold from South America. *In*: Fitzpatrick, R.W. & Donnelly, L.J. (eds) *Forensic Soil Science and Geology*. Geological Society, London, Special Publications, **492**, https://doi.org/10.1144/SP492-2018-15

Donnelly, L.J. 2002*a*. *How Forensic Geology Helps Solve Crime. All-Party Parliamentary Group for Earth Science*. House of Commons, Westminster Palace, 12 March 2002.

Donnelly, L.J. 2002*b*. Finding the silent witness: how forensic geology helps solve crimes. All-Party Parliamentary Group for Earth Science. *Geoscientist*, **12**, 24.

Donnelly, L.J. 2003. The applications of forensic geology to help the police solve crimes. *European Geologist*, **16**, 8–12

Donnelly, L.J. 2005. *Considerations for a Geological Society of London, Forensic Geology Specialist Group. The Geological Society, London. Submitted to the Geological Society of London, Executive Secretary and Science Council, December 2005*. Geological Society, London.

Donnelly, L.J. (ed.) 2006. First inaugural meeting of the Geological Society of London, Forensic Geoscience Group. Geoscientists at Crime Scenes. Forensic Geoscience Group Meeting, 20 December 2006. Geological Society, Forensic Geoscience Group, London.

Donnelly, L.J. 2008. Considerations for a Working Group on Forensic Geology. Submitted to the International Union of Geological Sciences, Commission for Geoenvironmental Management, 5th Annual Business Meeting of IUGS-GEM, Oslo, 8–9.

Donnelly, L.J. 2009*a*. *Establishment of an International Working Group on Forensic Geology*. The International Union of Geological Sciences, Geosciences for Environmental Management, Montevideo, Uruguay, 12 October.

Donnelly, L.J. 2009*b*. The geological search for a homicide grave. *The Investigator*, 42–49.

Donnelly, L.J. 2010*b*. IUGS-GEM Proposal: *A Guide to Forensic Geology*. Working Group on Forensic Geology Geological Survey of Namibia/Ministry of Mines & Energy. The International Union of Geological Sciences, Geosciences for Environmental Management. Tuesday 5 October 2010. Windhoek, Namibia. Breakout Session.

Donnelly, L.J. 2011. International Union of Geological Sciences (IUGS), Commission on Geosciences for Environmental Management (GEM). Report on Working Group on Forensic Geology (WGFG) and Establishment of the IUGS Initiative on Forensic Geology. Submitted to 62nd Executive Committee of the IUGS. UNESCO Headquarters, Paris, 22nd February.

Donnelly, L.J. 2013. Use of geology in forensic science: search to locate burials. *In*: Elias, S.A. (ed.) *The Encyclopedia of Quaternary Science*. Elsevier, **4**, 521–534.

Donnelly, L.J. (ed.) 2017. *Episodes Journal of International Geoscience*. Special Issue on Forensic Geology, **40**, June.

Donnelly, L.J. 2018 *House of Lords, Select Committee on Science & Technology: Forensic Science, Call for Evidence*. International Union of Geological Science, Initiative on Forenic Geology, 13 September.

Donnelly, L.J. 2020. Standard Operating Procedure (SOP) for soil sampling for the detection of volatile organic compounds (VOC) and leachate associated with human decomposition from a shallow, unmarked, homicide grave. *In*: Fitzpatrick, R.W. & Donnelly, L.J. (eds) *Forensic Soil Science and Geology*. Geological Society, London, Special Publications, **492**, https://doi.org/10.1144/SP492-2020-58

Donnelly, L.J. 2021. Introduction. *In*: Donnelly, L.J., Pirrie, D., Harrison, M., Ruffell, A. & Dawson, L. (eds). *A Guide to Forensic Geology*. Geological Society, London, 1–5, https://doi.org/10.1144/GFG.1

Donnelly, L.J. & Harrison, M. 2010. *Development of Geoforensic Strategy & Methodology to Search the Ground for an Unmarked Burial or Concealed Object. Emergency Global*. Barclay Media Ltd, 30–35, July.

Donnelly, L.J. & Harrison, M. 2013. Geomorphological and geoforensic interpretation of maps, aerial imagery, conditions of diggability and the colour coded RAG prioritisation system in searches for criminal burials. *Geological Society, London, Special Publications*, **384**, 173–194, https://doi.org/10.1144/SP384.10

Donnelly, L.J. & Harrison, M. 2015. A collaborative methodology for ground searches by a forensic geologist and law enforcement (police) officer: detecting evidence related to homicide, terrorism and organized crime. *Proceedings of the 3rd International Conference on Engineering Geophysics, Session on Forensic Geosciences*, Al Ain, UAE, FG02, 260–268.

Donnelly, L.J. & Harrison, M. 2017. Ground searches for graves and buried targets related to homicide, terrorism and organised crime. *In*: Donnelly, L.J. (ed.) *Episodes Journal of International Geoscience*. Special Issue on Forensic Geology, International Union of Geological Sciences, **40**, 106–117, June 2017.

Donnelly, L.J. & Harrison, M. 2020. The Geoforensic Search Strategy: a high assurance search method to assist law enforcement locate graves and contraband associated with homicide, counter terrorism and serious and organised crime. *Journal of the Geological Society of Japan*, **126**, 443–458.

Donnelly, L.J. & Harrison, M. 2021. Geoforensic Search Strategy (GSS): ground searches related to homicide graves, counter-terrorism and serious and organized crime. *In*: Donnelly, L.J., Harrison, M., Pirrie, D., Ruffell, A. & Dawson, L. (eds) *A Guide to Forensic Geology*. Geological Society, London, 19–79, https://doi.org/10.1144/GFG.3

Donnelly, L.J. & Murray, R. 2021. A historical overview of forensic geology. *In*: Donnelly, L.J., Harrison, M., Pirrie, D., Ruffell, A. & Dawson, L. (eds) *A Guide to Forensic Geology*. Geological Society, London, 5–18, https://doi.org/10.1144/GFG.2

Donnelly, L.J. & Ruffell, A. 2017. The Geological Society of London (GSL), Forensic Geoscience Group (FGG): the first decade, 2006–2016. *Geoscientist*, **26**, 10–15, December 2016/January 2017, https://www.geolsoc.org.uk/Geoscientist/DecemberJanuary-2016-17/Forensic-Geoscience-Group-the-first-decade

Donnelly, L.J. & Ruffell, A. 2021. Emerging applications of forensic geology. *In*: Donnelly, L.J., Harrison, M., Pirrie, D., Ruffell, A. & Dawson, L. (eds) *A Guide to Forensic Geology*. Geological Society, London, 165–181, https://doi.org/10.1144/GFG.8

Donnelly, L.J., Cassella, J. et al. 2019. Analysis of soil following a police-led open area search and the Recovery of a cold case homicide grave. *In*: Fitzpatrick, R.W. & Donnelly, L.J. (eds) *Forensic Soil Science and Geology*. Geological Society, London, Special Publications, **492**, https://doi.org/10.1144/SP492-2017-337

Donnelly, L.J., Pirrie, D., Harrison, M., Ruffell, A. & Dawson, L. (eds). 2021. *A Guide to Forensic Geology*. Geological Society, London, https://doi.org/10.1144/GFG.1

Ehrenberg, C.G. 1856. *Mikrogeologie*. Teil 2. Voss, Leipzig.

Fitzpatrick, R.W. 2008. Nature, distribution and origin of soil materials in the forensic comparison of soils. *In*: Tibbett, M. & Carter, D.O. (eds) *Soil Analysis in Forensic Taphonomy: Chemical and Biological Effects of Buried Human Remains*. CRC Press, Boca Raton, FL, 1–28.

Fitzpatrick, R.W. 2013*a*. Soils. *In*: Siegel, J.A. & Saukko, P.J. (eds) *Encyclopedia of Forensic Sciences*, 2nd edn. Academic Press, Waltham, MA, 206–212, https://doi.org/10.1016/B978-0-12-382165-2.00113-6

Fitzpatrick, R.W. 2013*b*. Soil: forensic analysis. *In*: Jamieson, A. & Moenssens, A. (Editors-in-chief) *Wiley Encyclopedia of Forensic Science*. John Wiley and Sons, Chichester, https://doi.org/10.1002/9780470061589.fsa096.pub2 (August 2013 updated articles), http://onlinelibrary.wiley.com/book/10.1002/9780470061589

Fitzpatrick, R.W. 2013*c*. Sampling and analyses of 6 soil samples relating to a burglary investigation by Victoria Police. *Centre for Australian Forensic Soil Science Restricted Client Report No. CAFSS_072*, 20 June.

Fitzpatrick, R.W. 2013*d*. Demands on soil classification and soil survey strategies: special-purpose soil classification systems for local practical use. *In*: Shahid, S.A., Taha, F.K. & Abdelfattah, M.A. (eds) *Developments in Soil Classification, Land Use Planning and Policy Implications: Innovative Thinking of Soil Inventory for Land Use Planning and Management of Land Resources*. Springer Science + Business Media, Dordrecht, 51–83, https://doi.org/10.1007/978-94-007-5332-7_2

Fitzpatrick, R.W. & Raven, M.D. 2012. How pedology and mineralogy helped solve a double murder case: using forensics to inspire future generations of soil scientists. *Soil Horizons*, **53**, 14–29, https://doi.org/10.2136/sh12-05-0016,

Fitzpatrick, R.W. & Raven, M.D. 2016. Guidelines for conducting criminal and environmental soil forensic investigations (version 10.1). *Report, CAFSS_076*. Centre for Australian Forensic Soil Science, Adelaide, Australia, https://www.adelaide.edu.au/directory/robert.fitzpatrick?dsn=directory.file;field=data;id=35757;m=view (accessed 11 February 2016).

Fitzpatrick, R.W. & Raven, M.D. 2019. The forensic comparison of trace amounts of soil on a pyjama top with hypersulfidic subaqueous soil from a river as evidence in a homicide cold case. *In*: Fitzpatrick, R.W. & Donnelly, L.J. (eds) *Forensic Soil Science and Geology*. Geological Society, London, Special Publications, **492**, https://doi.org/10.1144/SP492-2019-59

Fitzpatrick, R.W. & Riley, T.W. 1990. Abrasive soils in Australia: mineralogical properties and classification. Transactions of the 14th International Congress on Soil Science, Commission VII, Kyoto, Japan, 12–18 August. International Society of Soil Science, 404–405.

Fitzpatrick, R.W., Raven, M.D. & Forrester, S.T. 2009. A systematic approach to soil forensics: criminal case studies involving transference from crime scene to forensic evidence. *In*: Ritz, K., Dawson, L. & Miller, D. (eds) *Criminal and Environmental Soil Forensics*. Springer Science + Business Media, 105–127, https://doi.org/10.1007/978-1-4020-9204-6_8

Fitzpatrick, R.W., Raven, M.D. & Self, P.G. 2013. Sampling and analyses of 31 soil samples relating to a homicide investigation by South Australia Police at a property on Adelaide's northern outskirts. *Centre for Australian Forensic Soil Science Restricted Client Report No. CAFSS_095*, 17 May 2013, 80

Fitzpatrick, R.W., Raven, M.D. & Self, P.G. 2017. The role of pedology and mineralogy in providing evidence for 5 crime investigations involving a wide range of earth materials. *Episodes Journal of International Geoscience*, **40**, 148–156.

Gallagher, V., Knights, K., Carey, S., Glennon, M. & Scanlon, R. 2016. *Tellus Geochemical Survey Ebook Atlas 2016: Topsoil Geochemistry of the Northern Counties of Ireland. Data from the Tellus and Tellus Borders Project*. Geological Survey of Ireland.

Green, K.A., Caven, S. & Lister, T.R. 2010. Tellus soil geochemistry – quality assessment and map production of ICP data. *British Geological Survey Internal Report, IR/11/01*, 142

Guo, H., Wang, P. et al. 2019. A case study in forensic soil examination from China. *In*: Fitzpatrick, R.W. & Donnelly, L.J. (eds) *Forensic Soil Science and Geology*. Geological Society, London, Special Publications, **492**, https://doi.org/10.1144/SP492-2017-307

IUSS Working Group WRB 2015. World reference base for soil resources. World Soil Research. *Report 106*. FAO, Rome, http://www.fao.org/3/i3794en/I3794en.pdf

Johnston, R.M., Barry, S.J. *et al.* 2003, ASRIS: The database. *Australian Journal of Soil Research*, **41**, 1021–1036, https://doi.org/10.1071/SR02033

Khodakova, A., Smith, R., Burgoyne, L., Abarno, D. & Linacre, A. 2014. Random whole metagenomic sequencing for forensic discrimination of soils. *PLoS One*, **9**, e104996, https://doi.org/10.1371/journal.pone.0104996

Kobus, H. & Robertson, J. 2019. The importance of forensic soil science and geology being connected to mainstream forensic Science. *In*: Fitzpatrick, R.W. & Donnelly, L.J. (eds) *Forensic Soil Science and Geology*. Geological Society, London, Special Publications, **492**, https://doi.org/10.1144/SP492-2017-314

Kugler, W. 2003. X-ray diffraction analysis in the forensic science: the last resort in many criminal cases. JCPDS – International Centre for Diffraction Data. *Advances in X-ray Analysis*, **46**, 1–16.

Locard, E. 1930. Analyses of dust traces parts I, II and III. *American Journal of Police Science*, **1**, 276–298, 401–18, 496–514.

McDermott, S. 2013. Trace evidence: transfer, persistence and value. *In*: Siegel, J. (ed.) *Encyclopedia of Forensic Sciences*, 2nd edn. Academic Press, Waltham, MA.

McDonald, R. & Isbell, R.F. 2009. Soil Profile. *In*: *The National Committee on Soil and Terrain, Australian Soil and Land Survey Field Handbook*, 3rd edn. CSIRO, Melbourne.

McKinley, J. & Ruffell, A. 2019. Geographical information science (GIS), spatial sampling and sediment variability examined using a case of manslaughter. *In*: Fitzpatrick, R.W. & Donnelly, L.J. (eds) *Forensic Soil Science and Geology*. Geological Society, London, Special Publications, **492**, https://doi.org/10.1144/SP492-2018-16

Molina, C.M. & Pringle, J.K. 2019. Comparison of geophysical and botanical results in simulated clandestine graves in rural and tropical environments in Colombia, South America. *In*: Fitzpatrick, R.W. & Donnelly, L.J. (eds) *Forensic Soil Science and Geology*. Geological Society, London, Special Publications, **492**, https://doi.org/10.1144/SP492-2017-290

Morgan, R. & Bull, P. 2007. Forensic geosciences and crime detection: identification, interpretation and presentation in forensic geoscience. *Minerva Medicolegale*, **127**, 73–89.

Morgan, R., Cohen, J. *et al.* 2009. The relevance of the evolution of experimental studies for the interpretation and evaluation of some trace physical evidence. *Science and Justice*, **49**, 277–285, https://doi.org/10.1016/j.scijus.2009.02.004

Munsell Soil Color Book 2009. *Munsell Color Company*. Munsell Color X-rite, Michigan.

Murray, K., Fitzpatrick, R., Bottrill, R., Berry, R. & Kobus, H. 2016. Soil transference patterns on bras: image processing and laboratory dragging experiments. *Forensic Science International*, **258**, 88–100, https://doi.org/10.1016/j.forsciint.2015.10.009

Murray, K., Fitzpatrick, R., Bottrill, R. & Kobus, H. 2017. Patterns produced when soil is transferred to bras by placing and dragging actions: the application of digital photography and image processing to support visible observations. *Forensic Science International*, **276**, 24–40, https://doi.org/10.1016/j.forsciint.2017.03.026

Murray, R.C. 2004. *Evidence from the Earth: Forensic Geology and Criminal Investigation*, 1st edn. Mountain Press, Missoula, MT.

Murray, R.C. 2011. *Evidence from the Earth: Forensic Geology and Criminal Investigation*, 2nd edn. Mountain Press, Missoula, MT.

Murray, R.C. & Tedrow, J.C.F. 1975. *Forensic Geology*. Rutgers University Press, New Brunswick, New Jersey, 217pp

Pirrie, D., Donnelly, L.J., Rollinson, G.K., Butcher, A.R., Dawson, L.A. & Pirrie, D. 2013*a*. Forensic Geology at the International School Science Fair 2013. Geology Today. *Blackwell, The Geologists' Association & The Geological Society of London, Geology Today*, **29**, 224–230.

Pirrie, D., Ruffell, A. & Dawson, L.A. (eds) 2013*b*. *Environmental and Criminal Geoforensics. Geological Society, London, Special Publications*, **384**, https://doi.org/10.1144/SP384.17

Pirrie, D., Dawson, L. & Graham, G. 2017. Predictive geolocation: forensic soil analysis for provenance determination. *In*: Donnelly, L.J. (ed.) *Episodes Journal of International Geoscience*. Special Issue on Forensic Geology, **40**, 141–147.

Pirrie, D., Crean, D.E., Pidduck, A.J., Nicholls, T.M., Awbery, R.P. & Shail, R.K. 2019. Automated mineralogical profiling of soils as an indicator of local bedrock lithology: a tool for predictive forensic geolocation. *In*: Fitzpatrick, R.W. & Donnelly, L.J. (eds) *Forensic Soil Science and Geology*. Geological Society, London, Special Publications, **492**, https://doi.org/10.1144/SP492-2019-42

Pye, K. 2007. *Geological and Soil Evidence: Forensic Applications*. CRC Press, Boca Raton, FL.

Pye, K. & Croft, D. (eds) 2004. *Forensic Geoscience: Principles, Techniques and Applications*. Geological Society, London, Special Publications, **232**, https://doi.org/10.1144/GSL.SP.2004.232.01.01

Raven, M.D., Fitzpatrick, R.W. & Self, P. 2019. Trace evidence examination using laboratory and synchrotron X-ray diffraction techniques. *In*: Fitzpatrick, R.W. & Donnelly, L.J. (eds) *Forensic Soil Science and Geology*. Geological Society, London, Special Publications, **492**, https://doi.org/10.1144/SP492-2019-36

Report to the President 2016. Forensic science and the criminal courts: ensuring scientific validity of feature comparison methods, https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/PCAST/pcast_forensic_science_report_final.pdf.

Ritz, K., Dawson, L. & Miller, D. (eds) 2008. *Criminal and Environmental Soil Forensics*. Springer Science + Business Media.

Ruffell, A. & Barry, L. 2019. The desktop study – an essential element of geoforensic search: homicide and environmental cases (west Belfast, Northern Ireland, UK). *In*: Fitzpatrick, R.W. & Donnelly, L.J. (eds) *Forensic Soil Science and Geology*.

Geological Society, London, Special Publications, **492**, https://doi.org/10.1144/SP492-2017-333

Ruffell, A. & McKinley, J. 2008. *Geoforensics*. John Wiley and Sons, Chichester.

Salvador, F.A.S., Silva, P.N.E., Mascarenhas, R.D.O. & Rumbelsperger, A.M.B. 2019. The application of forensic geology to investigate the substitution of zinc ingots between China and Brazil. *In*: Fitzpatrick, R.W. & Donnelly, L.J. (eds) *Forensic Soil Science and Geology*. Geological Society, London, Special Publications, **492**, https://doi.org/10.1144/SP492-2018-83

Schoeneberger, P.J., Wysocki, D.A., Benham, E.C., Broderson, W.D. & Soil Survey Staff 2012. *Field Book for Describing and Sampling Soils*. Natural Resource Conservation Service, National Soil Survey Center, Lincoln, NE, version 3.0.

Science and Art 1856. Curious use of the microscope. *Scientific American*, **11**, 240.

Smith, P.A., Raven, M.D., Walshe, K., Fitzpatrick, R.W. & Pate, F.D. 2017. Scientific evidence for the identification of an Aboriginal massacre at the Sturt Creek sites on the Kimberley frontier of north-western Australia. *Forensic Science International*, **279**, 258–267, https://doi.org/10.1016/j.forsciint.2017.08.018

Soil Survey Staff 2014. *Keys to Soil Taxonomy*, 12th edn. United States Department of Agriculture Natural Resources Conservation Service, Washington, DC.

Stern, L.A., Webb, J.B. *et al.* 2019. Geographic attribution of soils using probabilistic modeling of GIS data for forensic search efforts. *Geochemistry, Geophysics, Geosystems*, **20**, 1–20, https://doi.org/10.1029/2018GC007872

Testoni, S.A., Melo, V.F., Dawson, L.A., Salvador, F.A.S. & Prandel, L.V. 2019. Evaluation of forensic soil traces from a crime scene: robbery of a safety deposit box in Brazil. *In*: Fitzpatrick, R.W. & Donnelly, L.J. (eds) *Forensic Soil Science and Geology*. Geological Society, London, Special Publications, **492**, https://doi.org/10.1144/SP492-2019-35

Wilding, L.P. 1994. Factors of soil formation: contributions to pedology. *In*: *Factors of Soil Formation: A Fiftieth Anniversary Retrospective*. Soil Science Society of America, Madison, WI, SSSA Special Publication, **33**, 15–30.

Wiltshire, P.E.J. 2009. Forensic ecology, botany and palynology: some aspects of their role in criminal investigation. *In*: Ritz, K., Dawson, L. & Miller, D. (eds) *Criminal and Environmental Soil Forensics*. Springer, 129–149.

Wiltshire, P.E.J. 2010. Forensic ecology. *In*: White, P.C. (ed.) *Crime Scene to Court: The Essentials of Forensic Science*. RSC Publishing, Cambridge, 54–85.

Wiltshire, P.E.J. 2015. *Protocols for Forensic Palynology*. Palynology. Taylor and Francis/The Palynology Society, 1–21.

Wiltshire, P.E.J. & Black, S. 2006. The cribriform approach to the retrieval of palynological evidence from the turbinates of murder victims. *Forensic Science International*, **163**, 224–230.

Wiltshire, P.E.J., Hawksworth, D.L., Webb, J.A. & Edwards, K.J. 2015. Two sources and two kinds of trace evidence: enhancing the links between clothing, footwear and crime scene. *Forensic Science International*, **254**, 231–242.

Young, J.M., Higgins, D. & Austin, J.J. 2019. Soil DNA: advances in DNA technology offers a powerful new tool for forensic science. *In*: Fitzpatrick, R.W. & Donnelly, L.J. (eds) *Forensic Soil Science and Geology*. Geological Society, London, Special Publications, **492**, https://doi.org/10.1144/SP492-2017-351