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Soil: Forensic Analysis

Introduction

Forensic soil science is the science or study of soil that involves the application of soil science, especially studies that involve soil morphology, soil mapping (assisted by existing soil maps and spatially held soil data), mineralogy, chemistry, geophysics, biology, and molecular biology to answer legal questions, problems, or hypotheses. *Soil science* is the term commonly used to study soil as a natural body in the landscape and as a resource to be managed for agricultural production, environmental waste disposal, and construction.

Soils mean different things to different people. Soil scientists (pedologists) view soils as being made up of different size mineral particles (sand, silt, and clay) and organic matter. Soils have complex biological, chemical, physical, mineralogical, and hydrological properties that are always changing with time. Hence, soil is dynamic, teeming with organisms, and is an integral part of the environment. Agronomists, farmers, and gardeners, on the other hand, see soil as a medium for growing crops, pastures, and plants – primarily in the top 50 cm of the Earth's surface. Engineers regard soil as material to build on and excavate, and are usually concerned primarily with moisture conditions and the capacity for soil to become compacted and support structures. However, some people regard soil as "dirt" or "mud" because it makes them "dirty" when they make contact with it.

Pedology (from the Greek *pedon* = soil), is the soil science discipline concerned primarily with understanding the variety of soils and their distribution, and is most directly concerned with the key questions concerning sampling, descriptions, processes of soil formation including the quality, extent, distribution, spatial variability, and interpretation of soils from microscopic to megascopic scales [1]. This description and interpretation of soils can be used in addressing the questions 'What is the soil like?' and 'Where does it come from?' (i.e., provenance determination) in studies relating to characterizing and locating the sources of soils to make forensic comparisons.

Forensic soil scientists are more specifically concerned with soils that have been disturbed or moved (usually by human activity), sometimes comparing them to natural soils, or matching them with soil databases, to help locate the scene of crimes. Forensic soil scientists usually obtain soil samples from crime scenes and suspected control sites from which soil may have been transported by shoes, a vehicle, or a shovel. Soil properties are diverse and it is this diversity, which may enable forensic soil scientists to use soils with a degree of certainty as evidence in criminal and environmental investigations [2, 3].

Forensic soil science is a relatively new activity that is strongly "method orientated" because it is mostly a technique-driven activity in the multidisciplinary soil areas of pedology, soil survey, soil mineralogy, soil chemistry, soil molecular biology, soil geophysics, and forensic science. There are few reviews of the specific application of one soil science discipline to criminalistics at the time of writing (i.e., apart from a recent series of publications by Fitzpatrick [2], Fitzpatrick *et al.* [3], Dawson *et al.* [4], and Ritz *et al.* [5]). Conversely, there are several wider-ranging and soil-related reviews, which provide comprehensive reviews of (i) "forensic geology" [6–12] and, (ii) "geoforensics", which focuses more on the geoscience techniques such as forensic geophysics, forensic remote sensing and geological trace evidence [13–15], and (iii) archaeology [16].

Soil materials are routinely encountered as evidence by police, crime scene investigators, and forensic staff. However, most forensic and physical evidence laboratories either do not accept or are unable to adequately characterize soil materials. The main reason for this is that the morphological, mineralogical, and spectroscopic analytical knowledge required to examine and interpret such soil evidence needs a large amount of training and expertise that is not yet available in most forensic science facilities. In recent years, soil science technology has advanced dramatically and become very specialized and, for this reason, scientists and police investigation units are not using soil information as much as they did previously (e.g., application mainly of petrographic microscope data). Currently, soil analyses are generally only performed in investigations of serious crime and usually where human DNA analyses or analyses of other more commonly used types of trace evidence were not possible. Consequently, there is an opportunity for the application of soil analysis in the forensic examination of soil from a wider spectrum of routine forensic investigations. This review outlines traditional and new soil methods, as well as systematic approaches for the forensic examination of soils.

Soil as a Powerful Contact Trace

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* [17], which states that when two surfaces come into physical contact there is a mutual exchange of trace evidence between them. For example, the exchange can take the form of soil material from a location transferring to the shoes of a person who walked through that location. These types of transfers are referred to as *primary transfers* (e.g., evidence is transferred from the soil surface to the shoe and later recovered from the shoe, such as in the treads of the sole or within the shoe). Once a trace material has transferred, any subsequent movements of that material, in this case from shoes (e.g., from the shoe to the carpet in a vehicles foot well), are referred to as *secondary transfers*. These secondary transfer materials can also be significant in evaluating the nature and source(s) of contact. Hence, the surface of soils can provide information linking persons to crime scenes. Higher order transfers (tertiary transfers) of trace evidence can also occur, which can present interpretative problems for forensic soil scientists because the ultimate source of trace evidence may be extremely difficult to identify.

Aardahl [18] lists the properties of the ideal trace evidence: (i) it is highly individualistic; (ii) it has a high probability of transfer and retention; (iii) it is nearly invisible; (iv) it can quickly be collected, separated, and concentrated; (v) the merest traces are easily characterized; and (vi) it is able to have computerized database capacity. In this context, glitter (i.e., entirely manmade tiny pieces of Al foil or plastic with vapor-deposited Al layer) has been considered to be the ideal contact trace [19]. Soil materials may be considered as approaching the ideal "contact trace", and the following brief discussion considers how closely they fulfill the criteria of Aardahl.

Soil is Highly Individualistic

Diversity of Natural Soils. It is important to understand and know the different kinds of soils and how they form because this helps in making accurate forensic comparisons. To determine the wide variety of soils that occur in the world, it is necessary to understand soil classification systems used to illustrate this. Soil classifications help to organize knowledge about soils, especially in conducting soil surveys. The two international soil classification systems, which are widely used, are the World Reference Base (WRB) [20] and Soil Taxonomy [21]. Many countries also have national and specialized technical classifications [22]. 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. Soil maps are produced at different scales to depict soils over (i) large areas such as the world, countries, and regions (1 : 100 000 or smaller scale), and (ii) detailed areas such as farms (1 : 10 000 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 (USDA), which collects soil data at many different scales, there are over 50 000 different varieties of soil in the United States alone. Parent material, climate, organisms, and the amount of time it takes for these properties to interact vary worldwide.

Anthropogenic Soils. Urban soils is a class of *anthropogenic* or *anthropic soils*, a term used in several soil classification systems [20] to indicate soils that are essentially under strong human influence in urban and suburban areas. They are 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 anthropic soils, which are also strongly influenced soils, but found away from cities. Anthropic soils are characterized by a great ecological heterogeneity, and show special distinctness of soil properties.

These specific soils also contain a large array of historical information, which has been proved very useful in understanding and quantifying soil differences in forensic soil comparisons.

The major question posed is how can soils be used to make accurate forensic comparisons when we know that both natural and anthropic soils are highly complex and that there are thousands upon thousands of different soil types in existence? The following key issues are especially important in forensic soil examination because the diversity of soil strongly depends on topography and climate, together with anthropogenic contaminants:

- Forensic soil examination can be complex because of the strong diversity and heterogeneity of soil samples. However, such diversity, heterogeneity, and complexity enables forensic examiners to distinguish between soil samples, which may appear similar to the untrained observer.
- A major problem in forensic soil examination is the limitation in the discrimination power of the standard and nonstandard procedures and methods.

No standard forensic soil examination method exists. The main reasons for this are that examination of soil is concerned with detection of both (i) naturally occurring soils (e.g., minerals, organic matter, soil animals, and included rock fragments) and (ii) anthropogenic soils that contain manufactured materials such as ions and fragments from different environments whose presence may impart soil with characteristics that will make it unique to a particular location [e.g., material from quarries, asphalt, brick fragments, cinders, objects containing lead from glass (*see* **Examination of Fibers and Textiles**), hydrocarbons, paint chips (*see* **Paint: Interpretation**), and synthetic fertilizers with nitrate, phosphate, and sulfate]. In spite of the increasing impact of human activities on soil and the likelihood that all of Earth's ecosystems have been influenced to some extent by humans, many soils still retain their basic morphology imparted by natural soil-forming processes. These anthropogenic properties make the naturally occurring soils even more individualistic.

Soil is Easy to Characterize: Large and Trace Amounts

Historical Analysis Methods for Forensic Soil Samples: 1856–1904. Soil materials are generally easy to characterize, especially by way of the following published historical examples, which demonstrate how large amounts of soil materials have been characterized using quick morphological and light optical methods to solve crime cases. On a Prussian railroad, in April 1856, a barrel which contained silver coins was found on arrival at its destination to have been emptied and refilled with sand. Prof Ehrenburg of Berlin acquired samples of sand from stations along railway lines and used a light microscope to match the sand to the station from which the sand must have come [22]. This is arguably the very first documented case where a forensic comparison of soils was used to help police solve a crime [2]. Then, in 1887, Sir Arthur Conan Doyle published several fictional cases involving Sherlock Holmes such as "A Study in Scarlet" in Beeton's Christmas Annual of London where Holmes can "Tell at a glance different soils from each other . . . has shown me splashes upon his trousers, and told me by their colour and consistence in what part of London he had received them". In 1891, in "The Five Orange Pips", Holmes observed "chalk-rich soil" on boots. This clearly indicates that Conan Doyle was well aware of the key soil morphological properties (color and consistence) and soil mineralogy (chalk) in forensic soil comparisons. Further, as documented by Murray and Tedrow [9, 10], "October 1904, a forensic scientist in Frankfurt, Germany named George Popp was asked to examine the evidence in a murder case where a seamstress had been strangled in a bean field with her own scarf. George Popp successfully examined soil and dust from clothes for identification to solve this real criminalistic case".

Standard/Traditional Analysis Methods for Forensic Soil Samples. The methods of soil analysis used in forensic science are predicated on the size of the sample and the use to which the analytical results will be put. The aim of forensic soil analysis is to associate a soil sample taken from an item (e.g., shoes, clothing, shovel, or vehicle) by police with a specific location. To achieve this aim, the methods of analyses chosen must be able to discriminate between soil samples from different locations. Importantly, the methods used for comparing the samples must be practical (use of standard methods), inexpensive, accurate, and applicable to small and large samples.

The methodology for describing soils has been developed and refined by soil scientists for more than a century [23]. Soils from crime scenes and control sites can be investigated at least in part with traditional soil survey descriptive approaches/techniques; however, these methods must be properly adapted and new methodology must still be developed [3].

Soil morphological descriptors such as color [24], consistency, structure, texture, segregations/coarse fragments (charcoal, ironstone, or carbonates), and abundance of roots/pores are the most useful properties to aid the identification of soil materials (e.g., [23, 25]) and to assess practical soil conditions (e.g., [26]). These soil morphological descriptions follow strict conventions whereby a standard array of data is described in a sequence, and each term is defined according to both the USDA Field book for describing and sampling soils, Version 2.0 [25] and National standard systems (e.g., Australian Soil and Land Survey Field Handbook by McDonald *et al.* [27].

Soil has a High Probability of Transfer and Retention

In general, soil usually has a strong capacity to transfer and stick, especially the fine fractions in soils (clay and silt size fractions) and organic matter. The larger quartz particles (e.g., >2-mm size fractions) have poor retention on clothes and shoes and carpets. Fine soil material (e.g., their <50–100-μm fractions) may often only occur in small quantities, as illustrated in a hit-and-run case illustrated by Fitzpatrick *et al.* [3], where a remarkably small amount of fine soil was transferred from a gravelly and stony soil on a river bank (control site) to running shoes (forensic evidence items).

Soil Can Quickly Be Collected, Separated, and Concentrated

Although soil forensic investigations are primarily performed in the laboratory, it should be emphasized that soil analyses typically begins at the crime scene and at the control sites. Hence, this section briefly summarizes the general procedures that will ensure that the collected samples are appropriate for the specific objectives of the forensic soil investigation. Soil samples must be carefully collected and handled at the crime scene or control sites using established approaches and then compared by a soil scientist with forensic science experience to ensure that the soil samples can be useful during an investigation. The size and type of samples to be taken are strongly dependent on the nature of the environment being investigated, especially the type of soil and nature of activity that may have taken place at the scene. For example, if suspect footwear is heavily coated with mud on the uppers and the ground is wet and soft, then the control sample should be collected to a depth of around 0–10 cm [3]. Samples of subaqueous soils or sediments from the bottom of river channels, streams, ponds, lakes, or dams can be obtained by pressing a plastic tube or container into the soft submerged soil/sediment and removing it with a scooping action. In deeper water, subaqueous soils/sediment samples can be taken using specialized sampling devices such as the Russian D-auger. In contrast, if the soil is very hard and dry and only the shoe tread was in contact with the soil, then carefully collect the 0–0.5 cm – or thinner. It is critical to wear clean latex gloves but do not use “talc powder” in the gloves because the layer silicate mineral “talc” will contaminate the soil sample. Always use clean tools (e.g., shovel, trowel, artist’s palette knife, which are made of stainless steel). Plastic spades and trowels generally lack the strength required to dig soils, especially for most Australian soil conditions. Artist’s palette knives are useful for sampling very thin layer surfaces of samples of mud or dust. Preferably place samples in “rigid plastic containers” – rather than polythene bags or paper bags because the package must keep soil lumps intact. Do not use paper envelopes because they easily tear and leak. If soil is adhering to items of clothing or shoes – first air dry the whole garment and then package whole intact sample and garment. If the soil is wet/moist or adhering in a wet/moist condition to objects (e.g., tires, vehicles, garments, or shovels) first air dry then package. However, as in the case of obvious sequential/chronologically deposited layers of soil being present, first remove the “surface layer” and then air dry. Store dry samples at room temperature and ensure containers are sealed and take appropriate caution when storing and transporting. If biological material is attached, package using clean cardboard box/paper bags because samples are prone to rapid deterioration.

Several standard methods are available for quick separation and concentration of soil materials or particles such as, for example, sieving, magnetic extraction, and heavy mineral separation (e.g., Figure 1).

Soil is Almost Invisible

Although a suspect may be unaware that soil material – especially the fine fractions (e.g., <50 μm) – has been transferred directly to the person (e.g.,

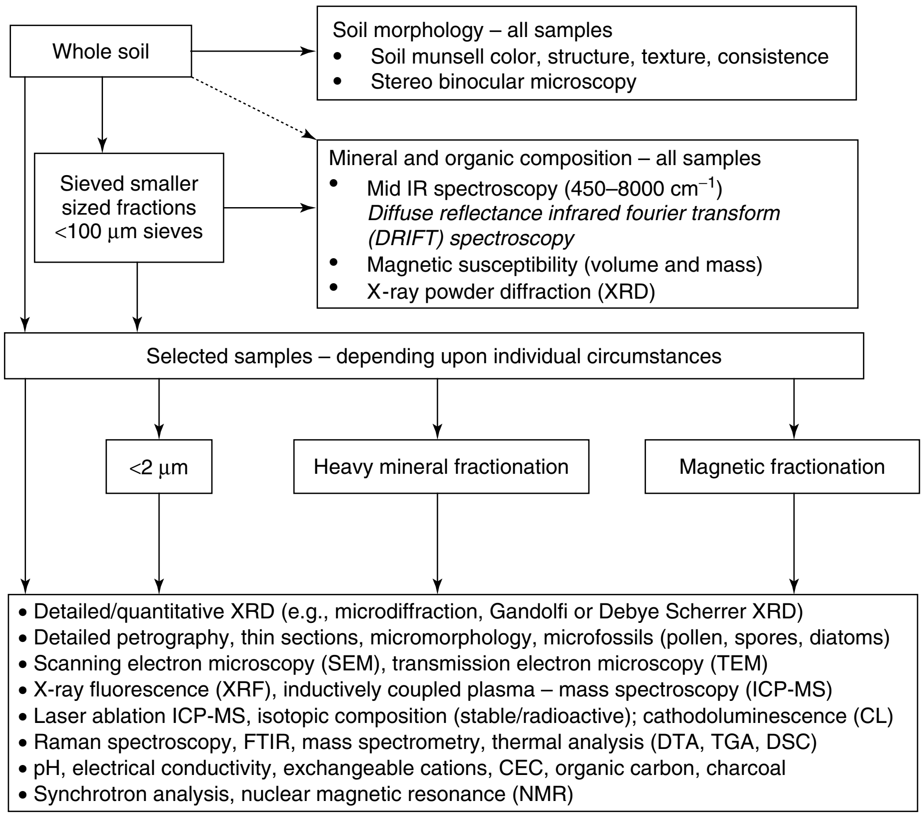

Figure 1 A systematic approach to discriminate soils for forensic soil examinations where FTIR is Fourier transform infrared spectroscopy, DTA is differential thermal analysis, TGA is thermogravimetric analysis, DSC is differential scanning calorimetry, and CEC is cation exchange capacity [3, 28]

shoes or clothing) or surroundings (e.g., carpet in a suspect's car), soil materials are easily located and collected when inspecting crime scenes or examining items of physical evidence [2–12]. Traces of soil particles can easily and quickly be located directly using hand lenses or light microscopes. For example, Fitzpatrick *et al.* [3] successfully completed a forensic comparison of small amounts of fine yellow–brown soil adhering to a suspect's shoe with a stony/gravelly black control soil submerged in a river where a hit-and-run offender ran through. Although the black-colored control soil comprised 95% alluvial stone and coarse gravel with only 5% clay and silt, a sufficient amount of fine yellow-brown material (<50 μm) was recovered by sieving. This fine soil material closely resembled the fine soil material that was tightly trapped in grooves and treads in the rubber sole of the suspect's shoe [3]. The control sample under typical viewing conditions by the naked eye did not readily observe the yellow-brown color of the fine 5% clay and silt (<50-μm fraction) fractions hidden in the extremely stony/gravelly soil until the sample was sieved and the fine fraction concentrated. This is, for example, often unlike the more obvious bright transfer colors of blood, lipstick smears, and paint chips (*see* **Paint: Interpretation**). Hence, if suspects cannot see fine soil materials adhering to their belongings, especially when they impregnate vehicle carpeting, shoes, or clothing, they will often make little effort to employ a comprehensive cleanup of soil materials.

Computerized Soil Database Capacity

Soil profiles and their horizons usually change across landscapes, and also change with depth in a soil at one location. In fact, soil samples taken at the surface may have entirely different characteristics and appearances from soil dug deeper in the soil profile. One common reason why soil horizons are different at depth is because there is mixing of organic material, in the upper horizons, and weathering and leaching, in the lower horizons.

Erosion, deposition, and other forms of disturbance might also affect the appearance of a soil profile at a particular location. For example, soils on alluvial flats with regular flooding often have clear sedimentary layers. Various soil-forming processes create and destroy layers and it is the balance between these competing processes that will determine how distinct layers are in a given soil. Some of the more common natural processes include the actions of soil fauna (e.g., worms, termites), and the depletion and accumulation of constituents including clay, organic matter, and calcium carbonate. In contrast, the main anthropogenic soil-forming processes that destroy layers are excavation (e.g., ploughing and grave digging) and fertilizer applications.

The mapping of the surface and subsurface of both natural and anthropogenic soils provides crucial information as to the origin of a site's specific location, function, land degradation, and management. In Australia, (e.g., [29]) and also in many developed countries in the world, soil data has been encoded into computer-compatible form. Hence, in Australia, for example, a soil map can be produced by downloading information directly from the Internet. The Australian Soil Resources Information System (ASRIS) database has compiled the best publicly available soil information available across Australian agencies into a national database of soil profile data, digital soil, and land resources maps, and climate, terrain, and lithology datasets. Most datasets are thematic grids that cover the intensively used land-use zones in Australia [29]. Hence, the first step when sampling across a region or wider area is to consult these existing/available soil maps of the region of interest in conjunction with or with help from experienced soil scientists. The areas of broadly similar soil type can then be identified as high priority areas for further sampling and comparative analyses – using morphological and analytical information. However, in the absence of obvious features, systematic sampling of the area should be conducted (cross-pattern to fully characterize the soil patterns in the area).

Common and Standardized Techniques Used by Forensic Soil Scientists

Evaluation of Degree of Similarity between Questioned Samples and Control Soil Samples

It is important to first define the word "compare" because no two physical objects can ever, in a theoretical sense, be the same [10]. Similarly, a sample of soil or any other earth material cannot be said, in the absolute sense, to have come from the same single place. However, according to Murray and Tedrow [10], it is possible to establish "with a high degree of probability that a sample was or was not derived from a given place". For example, a portion of the soil (or other earth material) could have been removed to another location during human activity. Pye [11] summarizes different schemes commonly used in the United Kingdom to convey weight of evidence relating to forms of comparisons such as trace or DNA evidence. For example, he has developed "verbal categories" ranging from 0 (no scientific evidence) to 10 (conclusive) – with no statistical significance of the ranks implied. He also states that there is a long history of the use of numerical scales in the context of evidential and legal matters.

Approaches and Methods for Making Comparisons between Soil Samples

Forensic soil scientists must first determine if uncommon and unusual particles, or unusual combinations of particles, occur in the soil samples and must then compare them with similar soil in a known location [2]. To do this properly, the soil must be systematically described and characterized using standard soil testing methods to deduce whether a soil sample can be used as evidence (Figure 1).

Methods for characterizing soils for a forensic comparison involve subdividing methods into three steps: (i) descriptive (morphological), analytical (Figure 1), and spatial information (e.g., mapping).

Soil characterization requires a multidisciplinary approach, which combines descriptive, analytical, and spatial information (e.g., mapping) steps in the following three stages:

Stage 1 – Rapid characterization of composite soil particles in whole soil or bulk samples for screening of samples (Figure 1).

Stage 2 – Detailed characterization and quantification of composite and individual soil particles following sample selection, size fractionation, and detailed mineralogical and organic matter analyses using advanced soil analytical methods (Figure 1).
Stage 3 – Integration and extrapolation of soil information from one scale to next, to build a coherent model of soil information from microscopic observations to the landscape scale (e.g., using existing soil maps or field mapping information). In forensic soil science, a provenance examination or determination, also known as geographic sourcing, has developed to identify the origin of a sample by placing constraints on the environment from which the sample originated.

Stage1: Initial Characterization of Composite Soil Particles in Whole Samples for Screening

In the initial screening or comparison examination of whole soil samples, soil morphology, low magnification light microscopy, X-ray diffraction (XRD), diffuse reflectance infrared Fourier transform (DRIFT) spectroscopy, and magnetic susceptibility (volume and mass) are used to compare samples *via* bulk morphology, mineralogy, and organic matter characterization.

Soil Morphology – Soil Profiling. Soil morphology is defined as the branch of soil science and pedology that deals with the description, using standard terminology, of *in situ* spatial organization and physical properties of soils regardless of potential land use. Soil morphological interpretation provides a visual, quick, and nondestructive approach to screen and discriminate among many types of forensic soil samples. Morphological soil descriptors are arguably the most common and probably the simplest – and it is for this reason that all samples are characterized first using the four key morphological descriptors of color, consistency, texture, and structure (Figure 1). In many respects, the soil resembles a sandwich with these easily observed characteristics and thickness, which conveys the concept of different soil layers with different properties. In soil samples from crime scenes and control sites in question where soil may have been transported, by vehicle, foot, or shovel, a complete visual description of the soil is essential because it serves as a basis for soil identification, classification [20, 21], correlation, mapping, and interpretation [2, 3].

A checklist of six key macromorphological descriptors has been compiled from standard techniques used in soil science (e.g., [23]) for assessing the soil properties for forensic examinations. Observations of depth changes in various properties are recommended: *viz* consistence, color, texture, structure, segregations/coarse fragments (carbonates and ironstone), and abundance of roots in the different layers or horizons.

The use of petrography is a major and often precise method of studying and screening soils for discrimination in forensics (Figure 1). For example, nearly 50 common minerals (e.g., gypsum), as well as several less-common minerals can easily be seen by the naked eye, but using a hand lens or low power stereo-binocular microscope (**Microscopy: Low Power**) enables the forensic soil scientist to better detect mineral properties (e.g., particle shape and surface texture) and provide more accurate mineral identification. The petrographic microscope (**Microscopy: High Power**) is also commonly available for studying microfossils (pollen grains, grass spores, opal phytoliths, diatoms [11, 16] (*see* **Diatoms**; **Microscopy: Low Power**); and thin sections of soil samples (resin impregnated), minerals, and rocks. Thin sections of soil materials are mounted on a glass slide and viewed with the petrographic microscope under different incident light conditions through its special attachments (e.g., [30]). Where possible, such micromorphological investigations are used to supplement and verify features in macromorphological descriptions. Macromorphological and petrographic descriptors are useful in assessing soil conditions because of the following:

- They involve rapid field and laboratory assessments. Other methods, such as more detailed mineralogy (see below) and geochemistry, are complex and more costly to carry out.
- They can be used to evaluate causes for variations in soil condition induced by weathering (that may range from recent to thousands, to millions, or even billions of years), anthropogenic activities, land management, hydrology, and weather conditions.

Mineral and Organic Matter Identification and Composition. Once a familiarity with the morphology of the materials has been achieved using visual and light microscopic methods, most of the mineralogical and organic matter components in a particular whole or bulk soil sample can be determined using the following three selected methods:

X-ray powder diffraction (XRD) methods. XRD methods are arguably the most significant for both qualitative and quantitative analyses of solid materials in forensic soil science [2, 3, 31]. Extremely small sample quantities (e.g., few to a few tens of milligrams) as well as large quantities can be successfully analyzed using XRD. The critical advantage of XRD methods in forensic soil science is based on the unique character of the diffraction patterns of crystalline and even poorly crystalline soil minerals. Elements and their oxides, polymorphic forms, and mixed crystals can be distinguished by nondestructive examinations. Part of the comparison involves identification of as many of the crystalline components as possible, either by reference to the International Centre for Diffraction Data (ICDD) Powder Diffraction File [31], or to a local collection of standard reference diffraction patterns, coupled with expert interpretation [2, 3, 31, 32].

Diffuse Reflectance Infrared Fourier Transform (DRIFT) method. The main advantages of DRIFT spectroscopy are that the analysis is nondestructive and can be rapidly applied, and that the mid-infrared portion of the electromagnetic spectrum is sensitive to organic materials, clay minerals, and quartz, due to absorption of infrared light at vibrational frequencies of the molecular functional groups [32–36]. As such, this technique is a powerful qualitative tool, which can then be used semiquantitatively to predict analytes of interest when combined with partial least-squares (PLS) (MIR-PLS) or other chemometric techniques (Stage 2).

A new rapid mid-infrared (MIR) spectroscopic method, coupled with chemometric approaches, specifically PLS (MIR-PLS) modeling has been developed by Janik *et al.* [33, 34] as applied to soils to predict soil physicochemical properties and has been routinely applied to rapidly screen and compare crime scene samples (Figure 1). Principal component analysis (PCA), which models the spectral signatures alone, is also a powerful discriminatory tool, providing an objective method of comparing the mid-infrared spectra of the soil samples being examined when enough samples are available for the technique to be viable.

Mass and Volume Magnetic Susceptibility Methods. Added to the above two rapid methods and techniques are the use of magnetic susceptibility methods, which should also always be used before moving to the more costly detailed methods (Stage 2), which require sample separation (Figure 1). Mineral magnetic techniques are a relatively recent development (post 1971) and have now become a very powerful and widely used research tool to characterize natural materials in landscapes (e.g., [37]).

Stage 2: Detailed Characterization of Composite and Individual Soil Particles

X-ray Diffraction (XRD) Methods. In many soil forensic case investigations, the amount of soil available for analyses (e.g., on clothing or soles shoes) may preclude routine bulk analyses. In such situations, it is best to use an XRD fitted with a system for analysis of extremely small samples (e.g., thin coatings or single particles of the order of 2–10 mg) loaded into thin glass capillaries or deposited onto Si low background holders for XRD analysis [38]. For analysis in a Gandolfi or Debye-Scherrer powder camera, extremely small specimens (e.g., single mineral particles and paint flakes) can be mounted on the end of glass fibers. Consequently, according to Kugler [31], X-ray methods are often the only ones that will permit further differentiation of materials under laboratory conditions. According to Murray [8], "Quantitative XRD could possibly revolutionise forensic soil examination". For example, XRD patterns can also be likened to finger print comparisons between soil samples and how closely they relate to each other [3]. However, what is the significance of the close similarity in XRD patterns to the degree of similarity in terms of mineralogical composition? If the two soil samples, for example, contain only one crystalline component such as quartz (i.e., silicon dioxide), which is very common in soils, the significance of the similarity and its evidential value in terms of comparison criteria will be low. If, however, the two soils contain four or five crystalline mineral components, some of them unusual, then the degree of similarity will be considered to be high [3].

Methods such as XRD, X-ray fluorescence (XRF), and DRIFT spectroscopy, whose results partially overlap, are used. These overlapping results confirm each other and give a secure result to the examination.

Scanning Electron Microscopes (SEM) and Transmission Electron Microscopes (TEM). Scanning electron microscopes (SEM) (*see* **Microscopy: Scanning Electron Microscopy**) and transmission electron microscopes (TEM) are frequently used to examine the morphology and chemical composition (*via* energy dispersive spectroscopy) of particles magnified to over 100 000 times their original size making them very useful for discrimination (e.g., [39–41]). Soil minerals, fossils, and pollen spores that occur in soils [42] can be described and analyzed in detail by SEM and TEM, and are therefore very useful indicators when studying soil samples (e.g., [11, 16, 39–41]).

Elemental Analysis. The following range of more prevalent instrumental techniques are frequently used to determine the inorganic constituents in soil samples: XRF, atomic absorption spectroscopy (AAS), inductively coupled plasma (ICP) spectrometry, inductively coupled plasma-optical emission spectrometry (ICP-OES) (sometimes called *ICP-AES*), inductively coupled plasma-mass spectrometry (ICP-MS), and neutron activation analysis (NAA) [4–12]. Several geochemical techniques, using isotope ratios and geochemical signatures have been utilized in forensic work (e.g., [43]).

Biological Methods. Fossil pollen grains (*see* **Palynology**) and grass spores are preserved in many soils that are not strongly acidic ($<$pH 4) or alkaline ($>$pH 6). These reproductive particles are produced in large amounts by trees, shrubs, and grasses [7–11, 16]. Opal phytoliths (silica-rich) and calcium phytoliths are mineral deposits that form in and between plant cells. Marumo and Yanai [42] used opal phytoliths to differentiate soils with similar mineralogy. As stated earlier, FTIR can be used to characterize soil organic constituents (fats, waxes, proteins, cellulose, hemicellulose, and lignin) in soils [4, 33–36]. Other emerging soil forensic methods such as (i) plant wax markers analysis are summarized in Dawson *et al.* [4], (ii) plant fragment DNA analysis [4], and (iii) microbial fingerprinting using a variety of molecular biological techniques to analyze the diversity in soil microbial communities for forensic soil comparison [4, 44]. Several soil forensic studies have been reported [44, 45] to show that a soil bacterial community DNA profile could be obtained from small samples of soil recovered from potential crime scenes (e.g., shoes or clothing) with the profiles being representative of the site of collection.

Combined Methods. All these techniques and others listed in Figure 1 (e.g., heavy and magnetic mineral separations, routine soil chemical analysis, laser ablation, Raman spectroscopy, thermal analysis, NMR, and synchrotron analysis) in combination achieve reliable, definite, and accurate results, and provide additional information about the mineralogical, chemical, and physical properties of the suspected soil material.

Stage 3: Landform and Soil Mapping

Integration and extrapolation of soil information are necessary because soils from the crime scene and control site may constitute a highly variable continuum. Hence, integration of published soil maps or field mapping information together with other spatially held information, such as (i) terrain analysis Digital Elevation Model (DEM), (ii) regolith, geological, or vegetation maps, and (iii) remote sensing or geophysics data [13–15] are designed to study relationships between soils, landforms, and/or the stratigraphy of parent materials. This information will also ensure (i) better-informed sampling (i.e., pedometric testing of how "similar" soil on a suspect's shoe is to a scene of crime [46]), and (ii) construction of a coherent model of soil information from microscopic observations to the landscape scale (e.g., physical, chemical, or biological mechanistic process models). Decision making in forensic soil science is sometimes guided by mechanistic process models describing processes with physical, chemical, or biological mechanisms [2–15]. Some models use multiple data layers as spatial input. The data required for the analysis are frequently found in and extracted from soil and environmental databases such as geographic information systems (GISs).

Soil, regolith, and geological maps are commonly being used by forensic soil scientists in developing models to predict where sites of particular soil materials are located. An example of this relationship is from the staff in the Centre for Australian Forensic Soil Science (CAFSS) using soil maps and conducting field soil survey investigations to solve a double murder case [47, 48]. Morphological, chemical, physical, and mineralogical properties were used to identify similarities between soil found on a shovel taken from the suspect's vehicle and soil subsequently located in a quarry. Samples were indistinguishable or strongly matched in terms of all comparison criteria used, thus revealing the location of two buried bodies.

Forensic soil examination can be complex because of the diversity and heterogeneity of soil samples. However, such diversity and complexity enables forensic examiners to distinguish between soils, which may appear to be similar. There is a general lack of expertise in this relatively new area among soil scientists. For research and practical application in this area to grow appreciably, it will need to be considered and taught as an integral part of both soil science and forensic science courses [2, 3]. Finally, an attempt should be made to develop and refine methodologies and approaches to develop a practical "soil forensic manual with soil kit for sampling, describing, and interpreting soils" [3].

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