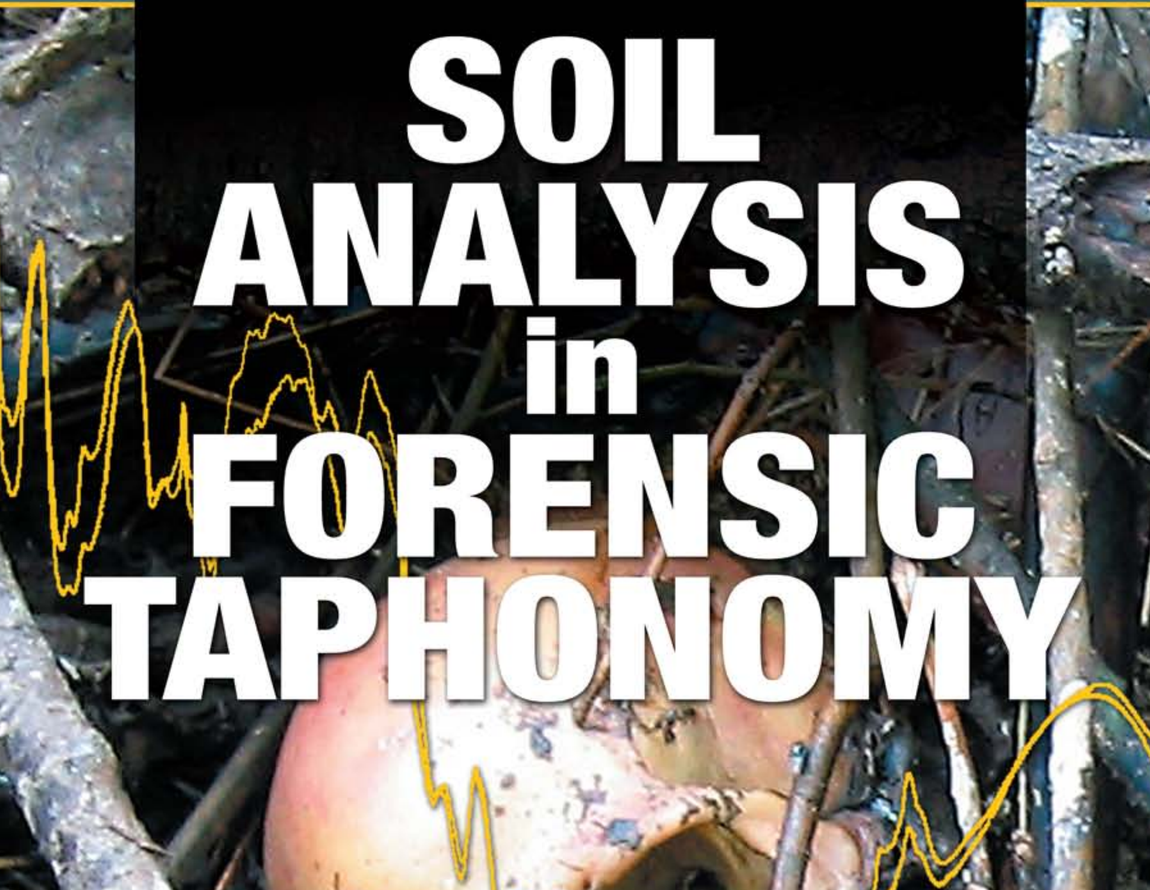
SOIL ANALYSIS in FORENSIC TAPHONOMY



Chemical and Biological Effects of Buried Human Remains

Edited by
Mark Tibbett and David O. Carter

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For Tammy, Jasmine, Courtney and Joseph.

M.T.

For my father and mother, who encouraged curiosity and my desire to learn. And to Mike Madison and the Hepworth family, for showing me the importance of study.

D.O.C.

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Preface

Forensic taphonomy is an applied discipline that is coming of age. To date, however, the major advances in the field have been captured in publications that deal primarily with the cadaver and associated items rather than the grave itself. This book provides, for the first time, a collection of chapters from leading scientists in their fields that deal primarily with the burial environment. Our focus is on the processes of decomposition in soils, the decomposers in the soil, and the basic physiochemical composition of the soil as it relates to forensic science and taphonomy.

The book aims to provide the reader with an up-to-date overview of fundamental scientific principles and methods used in forensic taphonomy from a soils-based perspective. Soils are the materials that make up most clandestine graves but are often given scant consideration. This is a shame, as soils can contain an enormous amount of information within them—if you know what to look for and how to find it. The purpose of this book is to illuminate this search for forensic information in the soils generally and at gravesites particularly. Of particular importance here is the detritusphere, the soil immediately around the cadaver. This soil is the most altered by the decomposition process and can contribute to the decomposition process. Many biological and chemical effects of buried human remains can be found here, and the analysis of soils around a cadaver for forensic use, though in its infancy, is progressing apace.

The terrestrial environment has been much studied as a decomposition environment for materials of little forensic value, such as leaf litter or dead roots. These provide the basic methods and framework for studying and understanding decomposition of materials in soils. It is only in recent years that this has been applied to forensic taphonomy, in which studies have been conducted with mammalian tissues and cadavers. The burial environment is a complex and dynamic system of interdependent chemical, physical, and biological processes. These processes influence, and are influenced by, the inclusion of a body and its subsequent decay. Though this book deals with what is known in this context, much still remains to be discovered, understood, and applied to forensic science.

We believe this book is timely, as soils are receiving increased attention as physical evidence. Thus far, the twenty-first century has seen an increase of peer-reviewed publications related to soils and forensic science of at least one third from the last decade of the twentieth century. We hope that this book will provide a solid foundation for forensic taphonomists, anthropologists, soil scientists, entomologists, bacteriologists, and mycologists who aim to use the processes of cadaver decomposition in terrestrial ecosystems to solve crime.

Mark Tibbett

David O. Carter

Editors

Mark Tibbett, Ph.D. is a soil microbiologist with a long-standing interest in decomposition processes in terrestrial ecosystems. He has worked in many of the world's ecoregions including tropical, Mediterranean, temperate, boreal, and polar ecosystems. His interests in forensic taphonomy arose from a research activity in organic nutrient patch dynamics in soils, the principles of which he has applied to forensic science. Dr. Tibbett is currently director of the Centre for Land Rehabilitation at the University of Western Australia.

David O. Carter, Ph.D. is an assistant professor of forensic science at the University of Nebraska-Lincoln, where he teaches courses in forensic science and coordinates the undergraduate degree program in forensic science. Dr. Carter earned a master of science in forensic archaeology from Bournemouth University, U.K. (2001) and a Ph.D. from James Cook University, Australia (2005). He investigates the processes associated with cadaver decomposition in terrestrial ecosystems with a focus on the fate of cadaver-derived carbon, nitrogen, and phosphorus to develop methods for the estimation of postmortem interval and the identification of clandestine graves.

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1 Nature, Distribution, and Origin of Soil Materials in the Forensic Comparison of Soils

ROBERT W. FITZPATRICK

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1.1 Introduction

Soils mean different things to different people. Soil scientists view soils as being made up of differently sized mineral particles (i.e., sand, silt, and clay) and organic matter. They have complex biological, chemical, physical, and mineralogical properties that are always changing with time. 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 ability of soil to become compacted to support structures. However, some people regard soil as *dirt* or *mud* because it makes them "dirty" when they make contact with it.

What do soils do for us? Soils provide a physical and chemical setting for gases, nutrients, and water. They also exchange heat for living organisms. In fact, biological activity, diversity, and productivity depend on the specific properties of soil. Soils also distribute surface water, causing runoff or infiltration, storage, and deep drainage. Consequently, water and solute flow on the earth's surface is primarily controlled by soils. Soil acts as sinks and filters, reducing contaminants that affect the quality of water and other resources. It also provides many construction materials (e.g., bricks) and is the foundation for urban and recreational facilities. In addition, soils are usually involved in the burial of human, animal, or plant remains in cemeteries or special kinds of landfills. Large-scale cadaver or plant decomposition processes are typically associated with such burial facilities. According to Dent, Forbes, and Stuart (2004) the discussion of human decomposition in soils has been largely untreated in detail, and the fragments available are often incomplete. The application of approaches and methods developed in pedology now are recognized by microbiologists, archaeologists, and forensic scientists as crucial to the understanding of human decomposition processes, burial site location, and questions relating to soil taphonomy.

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, and interpretations of soils from crime scenes. Pedologists are primarily interested in the way the five soil forming factors (i.e., parent material, climate, topography, organisms, and time) affect the properties of present and past (paleopedology) soils in both its natural and disturbed state. Soil surveyors, on the other hand, are interested in describing and classifying soils (using different National and International Soil Classifications Systems) and then mapping them, usually on aerial photographs with the aid of remote sensing techniques and geographic information systems (GIS). Forensic soil scientists (or forensic geologists) are more specifically concerned with disturbed or moved soils (usually by human activity) and sometimes with comparing them to natural soils or by matching them with soil databases to help locate the scene of crimes. Forensic soil scientists usually obtain soil samples from crime or polluted scenes and nearby suspected control sites from which soil may have been transported, by vehicle, foot, or shovel. Soil properties are diverse, and this diversity may actually enable forensic soil scientists to use soils as evidence with more certainty in criminal and environmental investigations.

Identification of soil differences by using various soil attributes is the first step for using soil information to help police and environmental investigators at crime scenes (i.e., including exhumations) and polluted sites, respectively. Unfortunately, pedologists often use quite difficult and convoluted terminology in soil classification (taxonomy) and for producing soil maps that are hard to understand or that will have little apparent relevance in forensic investigations. Pedological terminology is often difficult to understand, and a special education is needed to interpret it easily and meaningfully. A variety of unique terms is often used in soil reports and in legends to soil maps. However, work in the field and in the laboratory carried out by pedologists involves an assessment of a wealth of mainly soil morphological features that can readily be interpreted in relation to soil processes and so allows soils to be forensically compared.

This applied aspect is often obscured by preoccupation with using different national and international soil classification systems, especially for the "nonpedologist," so it is time to revisit the science of pedology and to reemphasize its interpretive value to forensic science. In recent years pedologists have developed several user-friendly special-purpose classification systems, covering for example the following variety of practical issues: (1) engineering applications (e.g., optical fiber cable and pipe installations); (2) minesoils; (3) soils used for viticulture and forestry; (4) saline and acid sulfate soils (links to policy and jurisdiction); (5) topdressing materials; (6) urban planning; and (7) mineral exploration (e.g., Fitzpatrick et al. 2003). These special-purpose or technical classification systems all involve soil assessment criteria and recommendations for soil management practices to end users. This chapter therefore has two principal objectives:

1. To review some established concepts and standard terminologies used in pedology that have practical relevance to forensic science and to in-soil human decomposition processes
2. To provide a brief example of the use of some pedological and related mineralogical methods in the forensic comparison of soils

1.2 Nature of Soils Relevant to Forensic Soil Science and Human Decomposition Processes

In 1910 the French scientist Edmond Locard, inspired by the *Adventures of Sherlock Holmes,* postulated the fundamental principle on which forensic science and trace evidence is based, namely, "The Locard Exchange Principle" (Chisum and Turvey 2000). When two things come into contact, physical components can be exchanged. For example, the exchange can take the form of soil from a location transferring to shoes of a person who walked through a particular area. These types of transfers are referred to as primary transfers. Once a trace material has transferred, any subsequent moves of that material are referred to as secondary transfers. These secondary transfer materials can also be significant in evaluating the nature and sources of contact. Hence, the surface of soils can provide information linking persons to crime scenes. The following key issues are especially important in forensic soil examination because the diversity of soil strongly depends on topography and climate, plus anthropogenic contaminants:

- Forensic soil examination can be complex because of the diversity and in-homogeneity of soil samples. However, such diversity and complexity enables forensic examiners to distinguish between soil samples, which may appear to be similar.
- 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 (1) naturally occurring soils (e.g., minerals, organic matter, soil animals, included rock fragments); and (2) manufactured materials in soils such as ions and fragments from different anthropogenic environments (e.g., synthetic fertilizers with nitrate, phosphate, and sulfate; artifacts or objects containing lead from glass, paint chips, asphalt, brick fragments, cinders) whose presence may impart soil with characteristics that will make it unique to a particular location. In addition, fine soil material may often only occur in small quantities, especially in the examination of materials from (1) the crime scene such as in Figure 1.1a, which shows a very small amount of yellowish-gray soil adhering to a suspects shoe, and (2) the control site such as in Figure 1.1b, which shows the complex diversity and in homogeneity of the soil sample from the bank of a river (Fitzpatrick, Raven, and Forrester 2007). The yellowish-gray soil at the control site comprises a mixture of 95% coarse gravel and rock fragments and only 5% clay and silt (< 50 μm fraction).

1.3 Brief History of Forensic Soil Science

On a Prussian railroad in April 1856, a barrel that contained silver coins was found on arrival at its destination to have been emptied and refilled with sand. A soil scientist acquired samples of sand from stations along lines of railway and used a light microscope to match the sand to the station from which the sand must have come (*Science and Art* 1856). This is arguably the

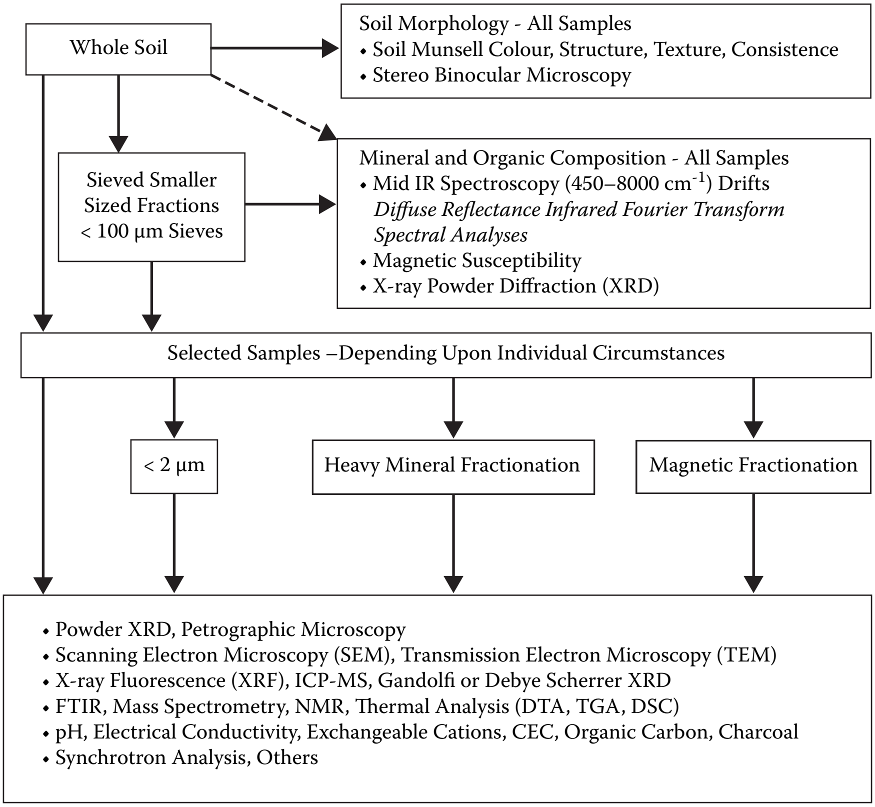

Figure 1.1 A systematic approach to discriminate soils for forensic soil examinations using soil morphology (e.g., thickness, color, consistency, texture, structure), organic matter, mineralogy, geochemistry (e.g., spectroscopy, magnetic susceptibility analyses), and wet chemical techniques (x-ray diffraction, XRD; inductively coupled plasma spectroscopy mass spectroscopy, ICP-MS; Fourier transform infrared spectroscopy, FTIR; nuclear magnetic resonance, NMR; differential thermal analysis, DTA; thermogravimetric analysis, TGA; differential scanning calorimetry, DSC; cation exchange capacity, CEC. (From Fitzpatrick, R. W., Raven, M., and McLaughlin, M. J., in R. W. Fitzpatrick (ed.), *Proceedings of the First International Workshop on Criminal and Environmental Forensics*, http://www.clw.csiro.au/cafss/, May 2006. With permission.)

very first documented case where a forensic comparison of soils was used to help police solve a crime.

Then in 1887 Sir Arthur Conan Doyle (Doyle 1981, p. 22) 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 color 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 (Doyle 1981, p. 217) was well aware of the key soil morphological properties (e.g., color and consistence) and soil mineralogy (e.g., chalk) in forensic soil comparisons. For the first time, as stated in Murray and Tedrow (1975), forensic scientist George Popp successfully examined soil collected from clothing associated with the murder of a seamstress named Eva Disch. Several recent reviews covering mainly "forensic geology" have been compiled by Ruffell and McKinley (2004) and Murray (2004). The issue of human decomposition processes in soils and the need to take into account the knowledge of soil environmental factors have been reviewed by several researchers (e.g., Dent et al. 2004; Garrison 2003; Spennemann and Franke 1995).

Forensic soil science is a relatively new activity that is strongly method oriented because it is mostly a technique-driven activity in the multidisciplinary areas of pedology, geochemistry, mineralogy, molecular biology, geophysics, archaeology, and forensic science. Consequently, it does not have an overabundance of past practitioners such as in the older disciplines like physics and chemistry.

1.4 Soil Origin, Classification, and Distribution

Pedology has two broad purposes: (1) to describe and classify; and (2) to interpret soil differences with respect to their management or use requirements. An appropriate definition of pedology is the area of earth science responsible for the quantification of factors and processes associated with soil formation (Wilding 1994). This includes the analysis of quality, distribution, and spatial variability of soils from micro- to megascopic scales (Wilding 1994). This definition introduces the phrase "extent, distribution, spatial variability, and interpretation" in a general way. It is fair to presume, though, that extent, distribution, spatial variability, and interpretation, for the pedologist, includes primarily the descriptive aspects of the science—the field and laboratory descriptions of soil attributes such as presence and degree of development of particular soil features (e.g., soil color, mottling) and the interpretive aspects of those attributes (e.g., soil in relation to drainage class or wetness). This description and its interpretation can then be explained in relation to the forensic comparison of soils. In addressing the questions, "What is the soil like?" and "Where does it come from?" (i.e., provenance determination), we are involved in studies relating to characterizing and locating the sources of soils to make forensic comparisons.

The sophistication and effectiveness of soil classification reflects the level of scientific maturity and an understanding of the particular area of study (Simonson 1959). A major aim of classification is to usefully summarize the natural variability of forms the entity takes and to enhance communication about that entity. However, soil classification may stimulate or may discourage scientists with an interest in soils.

If a classification system proves to be relevant and user friendly, it stimulates and encourages further work because it is recognized for its inherent capacity to create order and to enhance the useful understanding of soils (e.g., USDA 2003). This approach has provided numerous international soil scientists with valuable conceptual understanding of soils in terms of textural differentiation of profiles, the relative development of diagnostic horizons (e.g., gypsic, calcic, natric, argillic, oxic), subsoil color, and mottle differences. Many of the concepts in soil classification also provided effective pedotransfer functionality, particularly in terms of soil water attributes (e.g., Bouma 1989). If a soil classification is not useful it hinders transfer of information—often because of the lack of distinct separation between classes, many soils were inconsistently classified and distinguished, leading to conceptual confusion and pointless argument of subtle differences. For example, many soil classification systems are significantly biased toward agricultural soils, the subject of study for most soil scientists. Consequently, many soils found in nonagricultural environments are not suitably categorized because they do not match the central classification concepts (Fitzpatrick et al. 2003).

Soil classification systems are important tools within the context of the forensic comparison of soils. They are our attempts to bring conceptual order into the complex world of soils and to allow knowledge gained in one location to be used in another, given that we are transferring that knowledge to similar soil conditions with similar properties. The great variety of soils and climates makes classification a major task even if soils were changing. To appreciate the scale of the task we have to recognize that: soils are changing (e.g., due to erosion, salinization, disturbance, and oxidation of acid sulfate soils), their evolutionary history is only partially understood, and they are used for a range of purposes, all with unique requirements in relation to soil function and land use. The demands on soil classification are therefore so diverse that they cannot be satisfied by a single system at any point in time or for any part of the world. Changes in classification will be made with advances in data collection, storage, and processing, but their value depends on how easily class groups can be interpreted in relation to soil functions and processes. A sound basis for interpreting soils and their use in forensic soil comparisons resides in an improved understanding of soil processes and the interpretation of these from soil morphology in soil landscapes.

Soil formation, or pedogenesis, is a major activity for pedologists. The origins of soil attributes, distinctive horizons, and profiles must be understood to develop conceptual models for soil evolution over both long and short time periods (e.g., Smeck, Runge, and MacKintosh 1983). Such models have intuitive, predictive power in the forensic comparison of soils.

Factors of soil formation were proposed in the 1860s in the United States by E. W. Hilgard (Jenny 1961a) and in the 1880s in Russia by V. V. Dokuchaev (Krupenikov 1993) and have been developed in a semiquantitative fashion by Jenny (1941, 1961b, 1980), who formulated the now well-accepted *Clorpt equation*. Soil formation and the properties of the soil are the result of the following five key factors:

1. Parent material: The material from which the soil is formed. Soil parent material could be bedrock, organic material, an old soil surface, or a deposit from water, wind, glaciers, volcanoes, or material moving down a slope.
2. Climate: Heat, rain, ice, snow, wind, sunshine, and other environmental forces break down the parent material and affect how fast or slow soil processes proceed.
3. Organisms: All plants and animals living in or on the soil (including microorganisms and humans). The amount of water and nutrients plants need affects the way soil forms. Animals living in the soil affect decomposition of waste materials and how soil materials will be moved around in the soil profile. The dead remains of plants and animals (including human cadavers) become organic matter, which enriches soils. The way humans use soils influences soil formation.
4. Topography: The location of a soil in a landscape can affect how the climatic processes influence it. Soils at the bottom of a hill will get more water than soils on the slopes, and soils on the slopes that directly face the sun will be drier than soils on slopes that do not.
5. Time: All of these factors assert themselves over time, often over hundreds or thousands of years—but can even be hours (e.g., erosion; oxidation of pyrite to form sulfuric acid in acid sulfate soils).

Simonson (1959) proposed a more general framework for soil formation based on four groups of processes: additions, transfers, transformations, and removals. A dynamic approach to pedogenesis, building on the perspectives offered by Jenny (1941) and Simonson (1959), can be used to provide a framework for the assessment of soil properties at different spatial and temporal scales.

The way the five soil-forming factors interact differs from one place to another; accordingly, soils may differ greatly from each other. Each section of soil on a landscape has its own unique characteristics. The face of a soil, or the way it looks if one cuts a section of it out of the ground, is called a soil profile. Every soil profile is made up of layers called soil horizons. Soil horizons can be as thin as a few millimeters or thicker than a meter.

Usually, each soil layer or horizon is given a pedogenic notation (e.g., A, B, C) indicating its position in the soil profile and drawing attention to special features that may influence the use of the soil, such as surface layers or pans cemented by iron. Master pedogenic horizons or layers have the following features:

A1: Surface horizon, usually with higher organic carbon content
E: Paler subsurface horizon
B: Subsurface horizon, usually with more clay and brighter colors
C: Horizon with weathered rock or underlying sediment
R: Indurated rock layer
W: Water layers within or beneath the soil

Soils are often also discussed in terms of topsoil and subsoil. These terms are not rigorously defined, but denote the following:

- Topsoil: The surface zone, including the zone of accumulation of organic material (usually the A horizons). Topsoil can be modified by anthropogenic practices, such as road or foot traffic, plowing, and addition of fertilizers.
- Subsoil: Underlying layers (B and C horizons), which cannot usually be modified except by deep excavation (e.g., graves) and drainage

Soil descriptions follow strict conventions whereby a standard array of data is described in a sequence and each term is defined according to both the U.S. Department of Agriculture (USDA) Field book for describing and sampling soils, Version 2.0 (Schoeneberger et al. 2002) and national standard systems (e.g., McDonald et al. 1990). Soil morphological descriptors such as color, 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., Fitzpatrick et al. 2003) and to assess practical soil conditions (e.g., Yaalon and Yaron 1966).

Soil profiles and their horizons usually change across landscapes and also change as one digs deeper in the 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 that soil horizons are different as one digs deeper is the mixing of organic material in the upper horizons and weathering and leaching in lower horizons. Erosion, deposition, and other forms of disturbance might also affect the way a soil profile looks 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 and constituents including clay, organic matter, and calcium carbonate. In contrast, the anthropogenic soil-forming processes that destroy layers are excavation (e.g., plowing and grave digging) and fertilizer applications.

In natural conditions the speed of pedogenesis is such that it is barely perceptible within human generation spans. In anthropogenic conditions the speed, and direction, of pedogenesis can be altered through engineered effects on the soil forming factors and processes. Microclimate is modified by irrigation, fallows, and mulches; organisms are reselected and controlled for agriculture and forestry; relief is altered by land forming as leveling or contour bank construction; parent material is augmented with fertilizers and mulches but deprived by crop and residue removal. These modified factors in turn influence the rates of the soil forming processes. Fertilizers, tillage (erosion), crop removal, and irrigation (leaching fraction) alter the balance of additions and removals, whereas irrigation affects transfers within the system, for example by mobilization of free $CaCO_3$ in the upper part of the soil and precipitation deeper in the B horizon. Transformations such as humification/mineralization, mineral weathering, and clay degradation are all modified by the increased oxidation due to tillage, and hydrolysis due to changed moisture regimes. These human induced changes in pedogenesis have been referred to as metapedogenesis (Yaalon and Yaron 1966). In assessing soil for forensic comparisons or detecting buried objects (e.g., exhumations), metapedogenetic processes need to be clearly distinguished from the natural rate of pedogenesis.

1.5 Spatial Scale and Pedogenic Processes

Dijkerman (1974) suggested an organizational hierarchy, based on size, of seven subsystems for soil studies and discussed the relationship of empirical scientific methodology to these different levels. Other researchers (e.g., Hoosbeek and Bryant 1992; Sposito and Reginato 1992) adopted a similar approach. The pedon (Soil Survey Staff 1988) is accepted as the basic three-dimensional unit of soil encompassing the variations in horizon and profile features that would fully characterize the soil type under investigation. The pedon exists in the larger subsystem hierarchy of polypedon, toposequence, and catchment or region and contains smaller subsystems of horizons, peds, mineral organic complexes, and minerals. Investigation of soil at the pedon scale should always include details at the horizon scale and context at the toposequence or catchment scale (soil landscape). Description and quantification of attributes of subsystems, including their spatial variability, is advanced at all scales.

Soil assessment can therefore be related at all scales of pedological interest. However, the temporal variability of soils is less well understood or documented. Assessment of soil features and properties that may change in anthropogenic time scales requires clarification of rates of change of pedological attributes in response to pedogenic processes. Hoosbeek and Bryant (1992) reviewed progress toward the quantitative modeling of soil processes. They characterized models with respect to their relative degree of computation (qualitative to quantitative), complexity (functional to mechanistic), and level of organization (microscopic to megascopic). They concluded that although qualitative models have aided in soil survey and understanding soils in landscapes, there is a need to devise more quantitative models to predict how soils will change in the future. This is particularly important if soil properties are to be used in making forensic comparisons.

1.6 Relationship between Soil Type and Scale: Regional and Global

Typically, maps are used to provide pictorial representations of the distribution of soils, each map varying according to the specific soil classification scheme used. At levels above the soil profile scale in a soil landscape, or at small scales of investigation (1:250,000 and smaller) soil data become generalized, and soil comparisons for forensic purposes also become more generalized. Hence, map units at scales smaller than 1:50,000 cannot represent a single kind of soil. Reporting forensic soil comparisons using map data at these scales should only be used for intelligence (i.e., providing information for broad considerations) purposes and not for evidence. The reliability of such soil assessments depends on the density and quality of soil data collected at larger scales.

1.7 Most Favored Techniques Used by Forensic Soil Scientists

The major question posed now is how can soils be used to make accurate forensic comparisons when we know that soils are highly complex and that there are thousands of different soil types in existence? For example, according to the USDA, which collects soil data at many different scales, there are more than 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 will vary worldwide. First of all, soil samples must be carefully collected and handled at the crime scene and then compared by a soil scientist with forensic science experience to ensure that the soil samples can be useful during an investigation.

1.7.1 Theory of Making Comparisons between 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 (Murray and Tedrow 1991). 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 (1991) it is possible to establish "with a high degree of certainty that a sample is or is not associated with a given scene." For example, a portion of the soil (or other earth material) could have been removed to another location during human activity.

1.7.2 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 compare them with similar soil in a known location. 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 1.1).

Methods for characterizing soils for a forensic comparison involve subdividing them into two major categories: descriptive (morphological) and analytical (Figure 1.1). Morphological soil indicators 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 (Figure 1.1). In many respects, the soil resembles a sandwich with easily observed characteristics of thickness, color, consistency, texture, and structure, which convey the concept of different soil layers with different properties. In soil samples from crime scenes (polluted sites) and control sites in question where soil may have been transported—by vehicle, foot (e.g., Figure 1.2a), or shovel perhaps—and are suspect, these four visual properties are important indicators.

The following checklist of six key soil morphological descriptors has been compiled from standard techniques used in soil science (e.g., Schoeneberger et al. 2002) for assessing the soil properties for forensic examinations. These are: (1) observations of depth changes in consistence, (2) color, (3) texture, (4) structure, (5) segregations/coarse fragments (carbonates and ironstone), and (6) abundance of roots in the different layers or horizons. Morphological descriptors are useful in assessing soil conditions for the following reasons:

- They are rapid field and laboratory assessments. Other methods, such as mineralogy (see next section) and geochemistry, are complex and more costly to carry out.

Figure 1.2 Contact traces of yellowish-gray soil on the suspect's shoes (left) and the control soil specimen from the bank of a river (right), which comprises a mixture of 95% coarse gravel and rock fragments and only 5% clay and silt (< 50 µm fraction). (See color insert following p. 178.)

- They can be used in research to evaluate causes for variation in soil condition induced by anthropogenic activities, land management, hydrology, and weather conditions.

1.7.2.1 Soil Color

In particular, soil color should be determined on dry and moist samples using Munsell Soil Color Charts (1994). Soil color is usually the first property recorded in a morphological description of soils (and may be the only feature of significance to a layperson) and provides an indicator of redox status because soil color relates to soil aeration and organic matter content (Fitzpatrick, McKenzie, and Maschmedt 1999). Soil color has been found to be extremely useful in forensic soil identification by Sugita and Marumo (1996).

This more objective notion of soil color uses three coordinates: hue (shade), value (lightness), and chroma (intensity). Hue is the color frequency and in most soils ranges from red to yellow. Value or tone refers to lightness from white to black, and chroma defines the degree of color saturation or intensity of hue. Red soil matrices are generally described with hues 5 YR or redder (and chroma greater than 1), reddish with hues 7.5 YR (and chroma greater than 1), and yellow with hues 7.5 YR or yellower. Dark colors have low value (< 3) and low chroma (< 2). Training is recommended before consistent color matching is made (Post et al. 1993).

Color of soils depends on the type of iron oxides and content of organic matter (Bigham and Ciolkosz 1993). Uniform high chroma red and yellow colors (hues) indicate oxidizing conditions, and uniform low chroma colors (dark gray and blue tints) indicate reducing, waterlogged, or aquic conditions. Mixtures of bright red or yellow soil matrices with blotches of dark gray or bluish form one type of mottle and indicate periodic conditions of water saturation (USDA 1998; Vepraskas 1992). Red soils are nearly always better drained than yellow soils.

The content and type of iron oxide affects soil chemistry. Several workers (e.g., Scheinost and Schwertmann 1995) have shown that phosphate adsorption maxima increase from red (hematitic) to yellow (goethite-rich) soils. Consequently, because yellow soils in some regions are closely correlated to soil P sorption, soil color has been used to predict the likely need for phosphate applications.

1.7.2.2 Soil Consistence

Soil consistence is a measure of the strength and coherence of a soil. Soil consistence or consistency is also called rupture resistance and is a very readily observed feature in the field. Consistence of a soil material can be measured in the field by simply manipulating a piece of soil in the hand and determining the magnitude of force needed to cause disruption or distortion. Consistence is expressed as loose, soft, firm, very hard, and rigid (USDA 1993). Terms used to describe consistence vary depending on the moisture content of the sample tested (e.g., soft when dry versus friable when moist). Changes in soil consistence with depth (cm) are recorded in the field using the field description checklist sheet (Table 1.1). The magnitude of force needed to cause disruption or distortion by manipulating a piece of block-like (25 mm to 30 mm on edge) soil in the hand or under foot. Stress is applied along the vertical in-plane axis of the block-like piece of soil by compressing it between extended thumb and forefinger, between both hands, or between foot and hard, flat surface. Obvious factors that influence consistency include soil texture, mechanical compaction, organic matter content, cementing agents, and water content. It is for this reason that consistency is best measured or assessed when the soil is either dry (i.e., standard moisture content) or moist (Table 1.1). If the piece of block-like soil is less than 25 mm to 30 mm on edge, then corrections should be made for class estimates given in Table 1.2 (i.e., 10 mm block will require about one third the force to rupture it).

Changes in soil consistence are a useful surrogate measure for identifying restrictive layers because soil texture and structure are often difficult to measure consistently by inexperienced operators and because root abundance depends on other factors such as climate, vegetation type, soil fertility, and land management.

1.7.2.3 Soil Texture

Field soil texture reflects the proportion of sand (2–0.02 mm), silt (0.02–0.002 mm) and clay (< 0.002 mm) in soil (Table 1.2). Field or hand soil texture is determined in the field by the following procedure:

- Take a sample of soil sufficient to fit comfortably into the palm of the hand (separate out gravel and stones). Moisten soil with water, a little at a time, and work until it just sticks to your fingers and is not mushy. This is when its water content is approximately at field capacity.
- Continue moistening and working until there is no apparent change in the ball (bolus) of soil. This usually takes one to two minutes.
- Attempt to make a ribbon by progressively shearing the ball between thumb and forefinger.

The behavior of the worked soil and the length of the ribbon produced by pressing out between thumb and forefinger characterizes ten selected soil texture grades as shown in Table 1.2. This surrogate is used to estimate the following:

- Water and nutrient retention or leaching capacity: Coarse-grained sands have larger pores than those found in finer-textured soils. Consequently, coarse sands are typically drained rapidly and have a poor ability to hold water and nutrients. Loamy sands hold more water and nutrients, whereas the available water capacity and nutrient retention ability of clays are high.
- Depth to restricting layers or subsurface compaction that may affect root growth or water movement (e.g., subsurface compaction, structure decline): Sandy soils are generally more prone to subsurface compaction than finer-textured soils.
- Erodibility (e.g., sands are more easily eroded by wind): Grain size may also affect the susceptibility to erosion. Fine sand grains are easily transported by the wind. Coarser grains are heavier and require more force to be moved. Clay particles, though light and easy to transport, are often difficult to detach because they are bound together.

Consequently, a trend in the change of texture down a profile is frequently used to classify soils (e.g., Isbell 1996; Northcote 1979) because of its importance for plant growth and water movement.

Table 1.1 Interpreting Soil Consistence

Class Number		Consistence Classes Australiana/ U.S. Department of Agricultureb		Rupture Resistance on a 25–30 mm Fragment of Dry Soil	Consistence Test Inferred from Excavation Difficulty[b]	Environment Indication
		Dry[b]	Moist[b]			
1	Loose	Loose	Loose	Block-like piece not obtainable. Only individual sand grains can be picked up between thumb and forefinger. (0)	Can be excavated with a spade using arm-applied pressure. Neither application of impact energy nor application of pressure with the foot to a spade is necessary.	No restriction on root growth for annuals and perennials. No restriction on water movement.
2	Very weak to weak	Soft	Friable	Fails (i.e., crumbles) under slight force applied between thumb and forefinger. (< 8–20)	Arm-applied pressure to a spade is insufficient. Excavation can be accomplished quite easily by application of impact energy with spade or by foot pressure to spade.	Root growth of annuals and perennials is unrestricted. Slight restriction on water movement; water is usually available to most crops and trees.
3	Firm to very firm	Firm	Firm	Fails under moderate to strong force applied between thumb and forefinger. (20–80)	Excavation with spade can be accomplished, but with difficulty. Excavation is easily possible with a full length pick using an over-the-head swing.	Water flow can be restricted contributing to periodic waterlogging.

4	Strong to very strong	Very hard	Very firm	Cannot be ruptured between thumb and forefinger but can be by applying full body weight under foot. (80–800)	Excavation with a full-length pick using an over-the-head swing is moderately to markedly difficult. Excavation is possible in a reasonable period of time with a backhoe mounted on a 40–60 KW (50–80 hp) tractor.	Root growth of most species is restricted. Water flow may be restricted.
5	Rigid	Rigid	Rigid	Cannot be ruptured by blow with hammer. (> 800)	Excavation is impossible with a full-length pick using an over-the-head arm swing or with reasonable time period with a backhoe mounted on a 40–60 KW (50–80 hp) tractor.	Root growth of most species is severely restricted. Water flow is normally restricted.

Notes: Figures in parentheses are the force needed for failure in newtons. Two systems are used to describe soil consistence. Table 1.2 approximately correlates the two systems by using five classes with corresponding field tests and environmental indications. The force (expressed in newtons) required to fail a fragment of soil is calculated from the weight required to crush the fragment (expressed as in kg force) multiplied by 9.81, the gravitational factor. (a) The Australian system uses the concept of soil strength and is measured on a 20 mm piece of soil. The class names are the same for all moisture contents, but soil water status must be recorded. (b) The USDA system uses fragments of soil about 25–30 mm in size and has different class names for different moisture contents (dry and moist).

Table 1.2 Interpreting Soil Texture from Behavior of a Moist Bolus (Ball)

Texture	Code	Ribbon	Ball	Feel and Approximate Clay Content	Interpretation
Sand	S	nil	Coherence nil to very slight	Cannot be molded. Clay is < 5%.	Minimal physical restriction to root growth for annuals and perennials but has a moderate susceptibility to mechanical compaction. No restriction on water movement, but periodic soil moisture stress is common because water is drained very rapidly.
Loamy sand	LS	5 mm	Coherence nil to very slight	Cannot be molded. Clay is 5–10%.	As above
Clayey sand	CS	5–15 mm	Coherence very slight	Cannot be molded. Clay is 5–10%.	As above
Sandy loam	SL	15–25 mm	Coherence slight	Sandy to touch. Clay is 10–20%	Root growth of annuals and perennials is not restricted but has a high susceptibility to mechanical compaction. Very slight restriction on water movement; soil water is available to most crops and trees. Water drains from the soil readily but not rapidly.
Loam	L	25 mm	Coherent and rather spongy	Smooth feel; may feel greasy if organic matter is present. Clay is about 25%.	Root growth of annuals and perennials is not restricted with moderate susceptibility to mechanical compaction.
Silty Loam	ZL	25 mm	Coherent and rather spongy	As above but more silky feel	As above
Sandy clay loam	SCL	25–40 mm	Strongly coherent	Sandy to touch; medium-size sand grains visible in finer matrix. Clay is 20–30%.	As above
Clay loam	CL	40–50 mm	coherent and plastic	Smooth to manipulate. Clay is 30–35%.	As above

Light clay	LC	50–75 mm	plastic	Smooth to touch; slight to shearing between thumb and forefinger. Clay is 35–40%.	Root growth of annuals and perennials is frequently restricted with moderate susceptibility to mechanical compaction. Soil water is available to most crops and trees. Water flow is restricted contributing to periodic waterlogging.
Medium clay	MC	>75 mm	smooth plastic	Can be molded into rods without fracture; has some resistance to ribboning shear. Clay is 45–55%.	Root growth of most species is moderately to severely restricted but with low susceptibility to mechanical compaction. Water drains very slowly. This does not apply to self mulching or subplastic clays.
Heavy clay	HC	>75 mm	smooth plastic	Can be molded into rods without fracture; has firm resistance to ribboning shear. Clay is > 55%	As above

Texture qualifiers: used as a prefix to refine texture description		***The Texture Groups according to Northcote (1979)***	
Coarse sandy	Coarse to touch; sand grains can be seen with the naked eye	**1. The Sands**	sand (S), loamy sand (LS), clayey sand (CS)
Fine sandy	Can be felt and often heard when bolus is manipulated; sand grains seen under hand lens of 10 times magnification	**2. The Sandy Loams**	sandy loam (SL)
Gritty	More than 35% very coarse sand and very fine (1–3mm) gravel	**3. The Loams**	loam (L), sandy clay loam (SCL), silty loam (ZL)
Gravely	35–70% of gravel by volume	**4. The Clay loams**	clay loam (CL)
Stony	35–70% of stones by volume	**5. The Light Clays**	light clay (LC)
		6. The Medium-Heavy Clays	medium clay (MC), heavy clay (HC)

Source: Adapted from McDonald, R. C., Isbell, R. F., Speight, J. G., Walker, J., and Hopkins, M. S., *Australian Soil and Land Survey: Field Handbook*, 2nd ed., Melbourne, Australia: Inkata Press, 1990 (with permission).

1.7.2.4 Soil Structure

Soil structure relates to the way soil particles are arranged and bound together (Schoeneberger et al. 2002). Soil structure can easily be described from the visible appearance of in situ soil in a dry to slightly moist state by the presence or absence of the following:

- Peds (granular, lenticular, platy, blocky, polyhedral, columnar, and prismatic)
- Single grain or structureless
- Massive
- Slickensides (shiny, cracked, or grooved clay surfaces)

The size, shape, and nature of soil aggregates, peds, or slickensides play a major role in determining profile hydrology and the ease of root penetration.

Where soil particles are bound together in naturally formed aggregates (peds) separated by irregular spaces, the soil is described as having structure. The degree and nature of structural development is largely determined by clay mineralogy and organic matter content. Peds result from the natural subdivision of the soil by fine cracks to form either small (granular or polyhedral) or large blocks (columnar, prismatic, and platy). The cracks separating these peds do not usually have shiny slickensided surfaces, but ped size and development may range from weak to strong. Where peds are largely absent, the soil is described as being structureless. In a single-grained material, two thirds of a soil is composed of individual particles, which are not bound together (loose and incoherent). In a massive material, two thirds of the soil occurs in one large block with the particles being bound together (coherent).

Slickensides are easily observable shiny planes of weakness along which movement occurs in shrink–swell medium-to-heavy clay soils. These are shearing faults, which exist permanently in wet or dry expansive clays. They take the form of cracked, polished, or grooved surfaces, ranging from 10 mm to 200 mm across. Slickensides often run through the soil mass in many directions and may break the structure up into bowl-shaped blocks. They can move up to 25 mm per year. Hence, the frequency and size of slickensides present can quantify the potential capacity of the soil to shrink and swell (i.e., develop cracks when dry). Soils or soil layers with slickensides are highly impermeable to water movement, especially when they are moist and root growth is restricted.

1.7.2.5 Segregations and Coarse Fragments

Segregations are accumulations of distinct mineral particles such as iron oxides, calcium carbonate, and gypsum that have formed in soil. They occur in a variety of sizes, shapes, and forms and can be either soft or hard. In many parts of the world, these segregations are common and can have a major influence on soil chemical and physical properties.

Calcium carbonate commonly occurs either as masses and nodules. Hydrochloric acid (1M HCl) is commonly used in the field to confirm the presence of calcium carbonate in the soil (Schoeneberger et al. 2002). The reaction between acid and soil carbonate causes effervescence. This is known as the fizz test. Gypsum is often present as crystals, which glisten. They generally occur in lower rainfall areas and often indicate high electrolyte concentrations in soils. Coarse fragments include rock fragments, strongly cemented soil materials, and hard segregations, which are sized greater than 2 mm.

1.8 Petrographic and Other Advanced Techniques and Instruments

The use of petrography is a major and often precise method of studying and screening soils for discrimination in forensics. For example, nearly fifty common minerals as well as several less common minerals can easily be seen by the naked eye (e.g., gypsum), but using a lens or low-power stereo-binocular microscope enables the forensic soil scientist to better detect mineral properties and to provide more accurate mineral identification. The petrographic microscope is also a common instrument used to study thin sections of soil samples (resin impregnated), minerals, and rocks. Thin sections of soil materials are mounted on a glass slide and are viewed with the petrographic microscope under different incident light conditions through its special attachments (e.g., Stoops 2003).

A new rapid mid-infrared spectroscopic method called diffuse reflectance infrared Fourier transform spectra (DRIFTS), coupled with chemometrics, has been developed by Janik, Merry, and Skjemstad (1998) and routinely applied to rapidly screen and compare crime scene samples (Figure 1.1). Added to these rapid methods and techniques are the use of rapid mass and volume magnetic susceptibility methods, which should also always be used before moving to the more costly methods (Figure 1.1). 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., Thompson and Oldfield 1986).

X-ray diffraction (XRD) methods are arguably the most significant for both qualitative and quantitative analyses of solid materials in forensic soil science. Extremely minute sample quantities or tiny sample areas 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 ICDD Powder Diffraction File (Faber, Fawcett, and Goehner 2005) or to a local collection of standard reference diffraction patterns (e.g., Rendle 2004). For analysis in a Debye-Scherrer powder camera, extremely small specimens (e.g., paint flakes) can be mounted on the end of glass fibers. Consequently, according to Kugler (2003), x-ray methods are often the only ones that will permit further differentiation of materials under laboratory conditions. Methods such as XRD, XRF, and DRIFTS are used, whose results overlap. These overlapping results confirm each other and give a secure result to the examination.

Scanning electron microscopes (SEMs) and transmission electron microscopes (TEMs) are also frequently used to examine the morphology and chemical composition (via energy dispersive spectroscopy) of particles more than 100,000 times their original size, making them very useful. Soil minerals, fossils, and pollen spores that occur in soils and can be described and analyzed in detail by SEMs and TEMs and are very useful indicators when studying soil samples. All these techniques in combination achieve reliable, definite, and accurate results and provide additional information about the chemical and physical properties of the suspected material.

For example, the following soil analyses methods were required in a burglary case (Fitzpatrick et al. 2007). The first step was to visually compare the suspect soil specimen (i.e., adhered soil scraped from the soles and sides of the running shoes shown in Figure 1.2a) and control specimen (i.e., soil shown in Figure 1.2b, which was obtained from the bank of the river where the suspect was seen to run through). This visual comparison was conducted by eye and by low-power stereo-binocular microscope light microscopy. From these detailed visual observations, it appeared that the fine fraction in the riverbank sample had a similar yellow color to the soil adhered to the shoe. Consequently, because the riverbank sample contained more than 95% coarse gravel and stones, a subsample was sieved using a 50 μm sieve to obtain a finer fraction (< 50 μm). The fine soil fraction from the riverbank and soil on the shoe had a remarkably similar color (Munsell color) and mass magnetic susceptibility. Hence, in accordance with the systematic approach outlined in Figure 1.1, the third step was to check their mineralogical and chemical composition by using XRD and DRIFTS analyses.

The XRD diffraction patterns of the shoe (suspect) and riverbank (control) soil samples closely match each other—a technique that can be likened to fingerprint comparisons (Figure 1.3). However, what is the significance of this close match? If the two soil samples, for example, contain only one

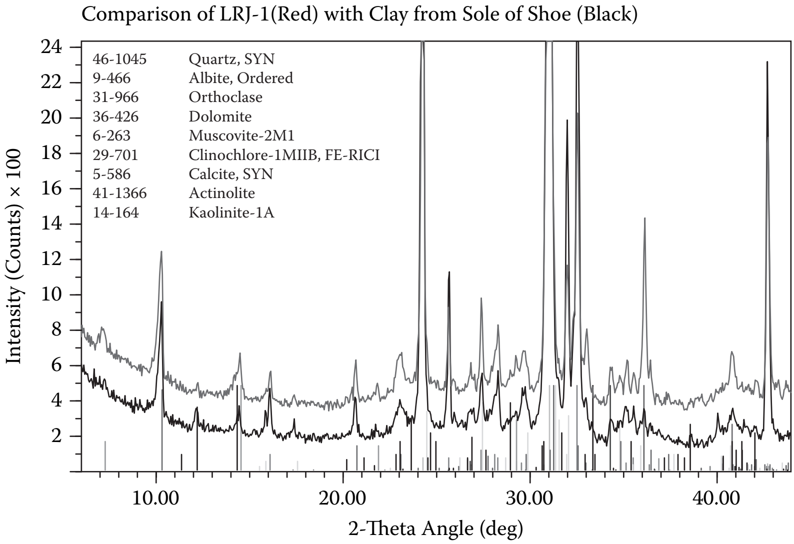

Figure 1.3 Comparisons between x-ray diffraction (XRD) patterns of soil samples from the shoe and riverbank (< 50 µm fraction) shown in Figure 1.2. The < 50 µm fraction was separated from the stony riverbank soil by sieving through a 50 µm sieve. Shoe and riverbank samples were both ground using an agate mortar and pestle before being lightly pressed into aluminum sample holders for XRD analysis. XRD patterns were recorded with a Philips PW1800 microprocessor-controlled diffractometer using Co Kα radiation, variable divergence slit, and graphite monochromator. (From Fitzpatrick, R. W., Raven, M. D., and Forrester, S. T., CSIRO Land and Water Client Report CAFSS_027, 2007. With permission.) (See color insert following p. 178.)

crystalline component such as quartz (i.e., silicon dioxide), which is very common in soils, the significance of the match and its evidential value will be low. If, however, the two soils contain four or five crystalline components, some of them unusual, then the significance of the match and its evidential value will be considered to be high. The mineralogical compositions of the two samples are summarized in Table 1.3 and are very similar; containing quartz, mica, albite, orthoclase, dolomite, chlorite, calcite, amphibole, and kaolin. Relative proportions of the minerals are slightly different, likely due to the different particle sizes of the samples.

DRIFTS analyses, or Fourier Transform Infraredspectroscopy (FTIR), was conducted on the same samples used for XRD analyses (Fitzpatrick et al. 2007). Light energy in the mid-infrared range (8000–450 cm^{-1}) is focused on the surface of the air-dried, finely ground soil samples. Some of the light beam penetrates a small distance into the sample and is reflected back into the spectrometer where the spectrum is collected. Although the two samples are spectrally similar (Figure 1.4) they do differ slightly in the amount of organic matter, which is reflected in some of broad peaks (i.e., because

Table 1.3 Summary of Mineralogical Composition from X-Ray Diffraction Analysis

Soil Samples	Quartz	Mica	Albite	Ortho-clase	Dolo-mite	Chlorite	Calcite	Amphi-bole	Kaolin
River-bank[a]	D	SDS	M	M	M	T	T	T	T
Shoe	D	M	M	M	T	T	T	T	T

[a] Where < 50 μm fraction; D, dominant (> 60%); SD, subdominant (20–60%); M, minor (5–20%); T, trace (< 5%)%).

Source: Adapted from Fitzpatrick, R. W., Raven, M. D., and Forrester, S. T., CSIRO Land and Water Client Report CAFSS_027, 2007 (with permission).

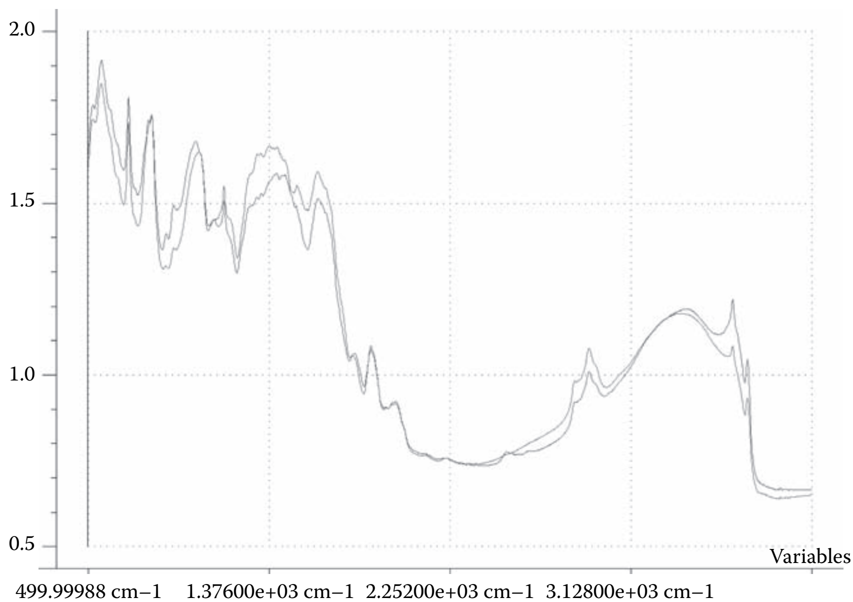

Figure 1.4 Comparison of diffuse reflectance infrared Fourier transform spectral (DRIFTS) patterns between the yellow-brown soil on the shoe (red) and the < 50 μm fraction in the stony soil from the riverbank (blue). Shoe and riverbank samples were both ground using an agate mortar and pestle. (From Fitzpatrick, R. W., Raven, M. D., and Forrester, S. T., CSIRO Land and Water Client Report CAFSS_027, 2007. With permission.) (See color insert following p. 178.)