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FORENSIC GEOLOGY

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Introduction

Forensic geology is concerned with the application of geological data and techniques in relation to issues which may come before a court of law. It is closely related to *environmental forensics, forensic engineering and forensic archaeology*. Environmental forensics is somewhat broader in scope than forensic geology and involves a wider range of environmental data, knowledge and expertise. It frequently involves investigations of environmental problems such as water and air pollution. Forensic engineering also overlaps with environmental forensics and is typically concerned with such issues as ground stability, the failure of buildings and other engineering structures, flooding, wind damage, fires and explosions.

All sub-disciplines of the geosciences have potential forensic applications, but sedimentology, mineralogy, petrology, geochemistry, palaeontology and geophysics have so far made the greatest contributions. Shallow geophysical prospecting methods have been widely used by forensic archaeologists and others to locate and characterize clandestine graves and buried objects such as drugs and weapons. However, probably the most widely recognized application of forensic geology is the use of geological materials as *trace evidence* which can be of value in linking a suspect to a crime scene. In the wider forensic and legal literature, sediment, soil, dust and rock fragments have often been grouped together under the loose term '*soil'* evidence.

Some of the earliest users of geological and soil evidence were in fact not geologists. As early as 1893 Hans Gross, an Austrian professor of criminology, had pointed out the value of examining ‘dirt’ on a suspect’s shoes as a possible indicator of their movements, and the German chemist Georg Popp is widely credited as being the first to undertake systematic ‘soil’ comparison studies in the early 1900’s. Around this time, the English fictional writer Sir Arthur Conan Doyle, literary creator of the investigator Sherlock Holmes, also utilized soil comparison in one of three cases in which he became a real life investigator. The work of these men had an important influence on Edmund Locard, initially a student of forensic medicine, who later went on to be Director of the Technical Police Laboratory in Lyons, France. Locard developed the first detailed scientific procedures for the analysis of dust traces, and established the famous Locard exchange principle:

Whenever two objects come into contact, there is always a transfer of material. The methods of detection may not be sensitive enough to demonstrate this, or the decay rate may be so rapid that all evidence of transfer has vanished after a given time. Nonetheless, the transfer has taken place.

In the United States, the Federal Bureau of Investigation Laboratory at Quantico, Virginia, was extensively using soil and mineral analyses in criminal cases as early as 1935, and has since maintained a strong interest in this area. Other important forensic work relating to particulates was undertaken in the 1960’s and 1970’s at McCrone Associates in Chicago, where the first Particle Atlas was developed. Outside the USA, scientists at the former UK Home Office Forensic Laboratory at Aldermaston, now closed, made extensive use of soil evidence in the 1960’s and 1970’s. In Japan, extensive use has been made of geological and soil evidence since the early 1980’s by scientists at the National Research Institute of Police Science.

Since the early 1990’s the true potential of geological and soil evidence, and that of other related sub-disciplines such as forensic botany, forensic entomology and forensic anthropology, has become much more widely recognized amongst police forces and forensic scientists worldwide. A much broader range of geological techniques and approaches is now being applied in the context of both criminal and civil law investigations. Many of these techniques also have extensive application in other areas, including the war against terrorism, international drug smuggling and broader environmental quality and public health campaigns. There is considerable current interest in applying forensic geological techniques and principles to such issues as illegal trading in ivory and rhino horn, archaeological artifacts and works of art, and in traceability studies related to a wide range of foodstuffs and other commodities.

Despite this long-standing interest, there is still only a relatively small specialist published literature in forensic geology, and until recently Murray and Tedrow's book 'Forensic Geology', originally published in 1975 and reprinted in 1992, was the only one available in the field.

Types of information provided by geological and soil evidence

There are many questions and issues to which forensic geological techniques and information can be applied. These include:

- was an individual, motor vehicle or other specified item present at a particular location (e.g. crime scene)?
- what was the sequence, and possible timing, of a visit to that location and possibly others?
- the location of buried objects (e.g. bodies, arms caches, drugs)
- the source of imported / smuggled items
- the cause of death (especially possible drowning and suffocation)
- the geographical origin of unidentified human remains
- the length of time a body has been present at a location, and length of post-mortem interval

Traces of rock, sediment, soil and dust can be present on a whole variety of items of interest, but amongst those most frequently submitted to the crime laboratory for examination are footwear, clothing, vehicles, flooring materials, digging implements, washing machine filters, polythene bags in which items have been stored, firearms and knives (Figures 1 and 2 near here). Samples associated with the human body are also sometimes subject to examination. These include tapings of the skin, finger-nail scrapings, washings from the hair, nasal passages, trachea and lungs, contents of the gastro-intestinal tract and faeces.

With modern analytical techniques, only very small traces of mud on an exhibit can provide ample sample material for a whole battery of tests to be undertaken (Figure 3 near here). However, the greater the amount of material which is available for analysis, the wider the options in terms of the analytical techniques which can be employed. If only small amounts of mud or particulates are present, there is usually a need to preserve as much of the evidence as possible for possible re-examination. Consequently non-destructive tests, or those which are minimally destructive, are preferable to destructive tests which require a relatively large amount of sample material.

Even exhibits which on first examination might seem unpromising from the viewpoint of preservation of forensic evidence, such as a burnt-out car (Figure 4 near here), can in fact be a source of useful geological evidence. Many geological materials are not affected by temperatures typically found in standard vehicle fires, and in many instances particles of gravel and sand can be recovered from suitable parts of such vehicles, such as the footwells and suspension arms.

Comparison of suspect samples with crime scene samples and other reference samples from known locations

One of the simplest situations faced by the forensic geologist is to compare mud or soil on a suspect's footwear or clothing with reference samples taken from a known crime scene. In most circumstances, comparison is also made with reference samples from one or more other locations (e.g. the suspect's home address or place of work) for elimination purposes. Comparisons of the samples should be based on several criteria, chosen from the list shown in Table 1, choice being dependent on a number of factors such as the amount and type of material present in the forensic samples, any available background information which might indicate which criteria are likely to provide best discrimination, and time, cost and equipment availability limitations. Clearly, the greater the number of lines of comparison which can be used, the greater is the potential for possible discrimination between samples. In some circumstances a single method of comparison may be sufficient to screen samples and to identify those which can be eliminated from further consideration. However, great care needs to be taken in selection of the screening method, since some soil and sediment properties, such as colour and particle size, may show considerable variation over short distances and also vary with time. As a general rule, at least three independent methods should be used for sample comparison, and considerably more may be required where an apparent similarity between 'suspect' and crime scene samples is identified.

Figure 5 (near here) shows an example of a soil-covered house brick which was recovered from a hold-all containing dismembered body parts found in a London canal. The identity of the victim was unknown and forensic examination of the hold-all showed it to be of a type widely available in the UK. Initial questions raised by the police therefore included whether anything could be said about the origin of the brick based on an analysis of the brick itself and also of the adhering soil. The approach in this case was to remove the soil and to analyse both the bulk material and different size fractions using a combination of several techniques. These included quantitative colour analysis, particle size analysis, mineralogical analysis, major and trace element analysis and pollen analysis. The results indicated the probable source as being a garden adjacent to a domestic property in a part of north London, and subsequent comparison with reference samples taken from the garden of a suspect who came into the enquiry showed a very high degree of similarity.

Figure 6 (near here) shows a boot with extensive red soil staining taken from the body of an illegal immigrant to the UK who was found in the wheel-well of a Boeing 747 aircraft which landed at London's Heathrow airport. The man carried no formal identification or indication of his origin. Since the plane had made a number of flights to several different countries in the time since the wheel well had last been subject to detailed examination, there were three possible places where the unidentified individual could have managed to stow away. In order to identify this location, red soil from the boots was examined using a combination of techniques including quantitative colour analysis, bulk sample and clay-fraction mineralogy by X-ray diffraction, chemical analysis by inductively coupled plasma spectrometry (ICP-OES and ICP-MS) and pollen analysis. The results clearly indicated a source in a wet tropical country. Comparison was made with control samples taken adjacent to the airport in the country (Ghana) from which the plane had last departed prior to its arrival at Heathrow, and a very high degree of similarity obtained in terms of all comparison criteria (Figure 7 near here).

The first stage in any forensic comparison of soil or other geological samples is to determine whether or not a possible 'match' can be excluded. If it can, then no further attention need be given to that sample. If it cannot, further investigation may be warranted. A conclusion of an exact match can sometimes be drawn with virtual certainty when the samples in question make a physical fit and have the same texture and chemical composition. This may occur, for example, with two halves or several broken pieces of fractured rock or ornamental stone. In other circumstances a physical fit may be observed, for example, between a shoe impression in mud and a shoe seized from a suspect which is of the same size and has the same tread pattern as that in the impression. However, there may be several thousand such shoes in circulation, and a specific 'match' with any individual shoe often cannot be made. In this instance, analysis of mud adhering to the shoe, if shown to be indistinguishable from that in which the shoe impression was found, may provide strong supportive evidence that the particular shoe under consideration formed the mark.

However, there any many occasions where mud-stained footwear is recovered during an investigation but an exact spot at a crime scene where it may have been acquired has not been identified. In such cases, comparisons of the soil on the shoe with several different reference samples from the crime scene, and usually also elsewhere, have to be made on the basis of statistical and graphical comparisons, and the results can only be interpreted in probabilistic terms. The degree of similarity between samples can be expressed in several semi-quantitative and quantitative ways, but meaningful statistics about the likelihood of such a degree of apparent 'match' being due to chance are often difficult to provide. This is because the full range of variation which exists in natural soils is impossible to determine, and can only be estimated on the basis of sampling. The availability of database information relating to suitable comparison samples varies greatly from one region to another, and there may be a total absence of pre-existing information in some parts of the world. In such cases, it is necessary for a suitable background investigation to be undertaken, involving collection and analysis of a sufficiently large number of reference samples, in order to provide adequate contextual information for interpretation.

Where no physical fit has been identified, the nearest thing to a definitive connection between two questioned samples is usually provided by the identification of one, but more commonly several, highly unusual (or 'exotic') particle types in both samples. These may be naturally-occurring particles or be of human or animal origin. They need not be considered 'unique' in themselves, but should be sufficiently rare, either alone or in combination with other unusual particles in the same sample, to make the chances of their occurrence in any two samples under investigation extremely low. Examples of two particles which fall into this category are shown in Figures 8 and 9 (near here). Waste-dumps, industrial premises and roadside verges are examples of locations which often contain mixtures of particles which have a more restricted distribution than in natural soils. The assemblages of particles present in such locations often show considerable local-scale variation, and it may be possible to limit a potential source area to just a few square metres.

Persistence of geological evidence

Geological evidence may persist for a considerable period of time after it has been picked up from the source location. For example, gravel, sand or mud which enters the interior of a car on footwear, clothing or other items, such as a spade, will stay there, subject to some loss due to outward transfer on the footwear or clothing of later occupants, until such time as the vehicle is thoroughly cleaned. Even after cleaning, traces may remain in certain hard-to-access locations. Whereas some forms of forensic botanical evidence degenerate due to oxidation or fungal decomposition, most inorganic sediment particles are very resistant and may be immune to changes over time. Consequently, they provide useful clues years or even decades after an initial crime was committed, providing that exhibits have been retained and suitably stored to prevent environmental and cross-exhibit contamination.

Modification of primary transfer soil evidence

It should always be borne in mind that material initially picked up from a location, a process referred to as *primary transfer,* may subsequently be modified as additional particles are picked up from other locations, or as some of the primary particles are lost during subsequent movement. During primary transfer, the material transferred may not exactly reflect the exact nature of the material at the source point, depending on the nature of the material and the nature of the contact involved. For example, if a person sits or lies on wet ground there is a frequent tendency for the finer particles to be selectively transferred and retained on the clothing. In other circumstances, only a certain size range of coarse particles may be retained, for example coarser particles trapped within the detail of footwear sole treads, or gravel particles trapped in tyre treads. For this reason, it is always important that sample comparisons are undertaken on narrowly defined size fractions as well as on bulk samples.

Secondary transfer

The possibility of *secondary transfer* of soil and other geological evidence should also always be borne in mind when exhibits are examined. For example, consider a case where Person A walks across a muddy car park and gets into the passenger seat of a vehicle and is driven by another person (B) to another location, where A gets out. During this process mud from the car park is transferred via the footwear of Person A to the front passenger footwell of the vehicle. The driver of the car (B) then drives to a third location and picks up another person, C, who also sits in the front passenger seat. The shoes of Person C come into contact with mud in the front passenger footwell deposited by Person A, and this is then transferred out of the car, via Peron C's footwear, onto the hallway carpet at Person C's home address. If it subsequently emerges that a crime has been committed at the car park, and Person C becomes a suspect, simple comparison of mud on Person C's footwear and hall carpet with control samples from the car park might lead to the spurious suggestion that Person C had been present at the crime scene. For this reason, great care needs to be taken by the forensic geologist to document the amount, distribution, layering and nature of any mud or similar evidence present on items, including footwear, submitted for analysis. In this connection there is an important responsibility on the part of police and scenes of crime examiners to provide the forensic geologist with necessary background information, and to ensure that comparison samples are taken from all locations and exhibits of possible relevance for comparative examination.

Location of crime scenes, buried bodies, weapons and drugs caches

A frequent problem which the forensic geologist is asked to address concerns identification of the location where a crime has taken place, perhaps involving disposal of a body, or where weapons, money and drugs have been stored or buried. In many instances one or more suspects are identified and their vehicles seized for possible identification of evidence which might indicate location of the deposition or burial site. Detailed examination of both the inside and outside of the vehicle is then undertaken, in parallel with searches for blood, other forms of DNA, fibres, hairs and fingerprints. Numerous samples are normally taken from the footwells, wheel arches, mud flaps and other parts of the bodywork and chassis to build up as detailed a picture as possible of the vehicle's recent movements. Similar examination and sampling is often undertaken on associated items such as petrol cans, car jacks, mats, spades, footwear and clothing belonging to the suspect. The samples are examined in terms of the full spectrum of their physical, chemical and biological make-up, the objective being to create an *environmental profile* of the samples which may assist the direction of further police enquiries.

In this type of work, individual particle types, which may either be inorganic or biological, can be highly diagnostic. Particular pollen types may indicate specific ecological habitats, such as moorland, coniferous forest, deciduous broad-leaf woodland, or saltmarsh. Diatom assemblages may indicate saline, brackish or freshwater environments. Highly diverse assemblages of particles of industrial / human origin may indicate waste dumps or industrial estates. Natural rock particles such as chalk, coal, slate and basalt, or minerals assemblages may indicate particular areas within specific geological outcrops. Even the abundance of different morphological types and surface textures of common minerals such as quartz may suggest specific localized areas with a particular surface geology and soil type (Figure 10 near here). Viewed in polished section under an optical or scanning electron microscope, rocks types which have very similar chemical composition can be seen to have quite different depositional and diagenetic textures which may be specific to particular litho-stratigraphic units only a few tens of millimetres in thickness (Figure 11). Such precise indentification is often aided by analysis of microfossil assemblages, including foraminifera, and shell debris.

Figure12 shows a number of gravel and coarse sand-size particles which were recovered at post mortem from the trachea and bronchi of a murder victim who had been shot in the head and whose burning body was found dumped on a farm track outside Edinburgh. The lithological assemblage of the gravel clasts, which were characterized by numerous *in situ* fresh water diatoms, indicated that they had originated from a river or river-marginal setting in the Airdrie area near Glasgow. The large size of the particles and depth of penetration into the lungs meant that they could only have been sucked in while the victim was alive, possibly being held face down with his head in water just prior to being shot.

Studies of human remains

Unidentified human remains are not infrequently found dumped by the roadside or are found washed up on the coast or in rivers and lakes. The remains may consist of whole bodies, with or without clothing, torsos or even isolated limbs. If identification proves impossible using dental records, fingerprints or DNA, alternative means must be used to determine the geographical origin and individual identity of the victim. Several ways exist in which the forensic geologist may contribute. First, studies of sand, mud and dust particles present on clothing or on the outside of the body may indicate the area from which the body came (Figure 13 near here). Particles which are exotic to the body discovery site, such as coralline algae on a body found in the United Kingdom, would clearly indicate a recent tropical or sub-tropical association. Studies of the pollen may provide further information about botanical exposure.

Studies of particles within the body may provide indications of environmental exposure in the hours or days immediately prior to death. Washings of nasal passages, lungs and hair may be useful in this way, as may fingernail scrapings and particulates contained within the gastrointestinal tract and faeces. Absence of exotic pollen and inorganic particles within the gastro-intestinal tract of a known recent immigrant may provide significant evidence that he or she had been present in the country where they were found for at least several days.

In cases where the cause of death cannot be determined with certainty by conventional post-mortem examination, examination of particulates in the lungs and other body tissues may assist in determining whether death was due to true drowning or some other cause prior to, or during, immersion. Analysis of diatoms present in the lungs, liver, spleen, blood and bone marrow has for many years been undertaken as a confirmatory test in possible downing cases (Figure 14 near here). However, the diatom test has been controversial since numerous cases of false negative and false positive results have been documented. However, if the test is combined with studies of other particles which are known to be associated with a particular water body or type, its reliability is potentially much improved. As previously noted, quite large quantities of particles up to fine gravel in size can be aspirated into the trachea and lungs through the open mouth in the presence of water. Such particles may also be swallowed and carried into the stomach of a drowning person. Water is not always required, however, and cases of death are quite frequent due to suffocation when dry silt, sand, soil or even fine gravel is forcibly or otherwise involuntarily inhaled. Careful analysis of diatoms and other environmentally-sensitive biotic indicators associated with the inorganic particles is a useful means of determining whether or not death occurred while the face was submerged in water. Similar environmental discrimination can be achieved with sediment and soil sometimes found in other body orifices of deceased persons, including the anus and vagina.

Analysis of the trace element and isotopic composition of nail, hair, bones and teeth can provide information about environmental exposure and diet over time periods ranging from a few days to an entire life span. Stable isotopes of carbon, oxygen, hydrogen and nitrogen provide information about diet, including drinking water, and hence about climate, while radiogenic isotopes of strontium, lead and neodymium, also reflect aspects of diet, geological source terrain and atmospheric exposure. In general, hair and nails provide information over time periods of a few days to a few months, bones provide information relating to the last few years of life, and tooth enamel provides information relating to the first few years of life, range from *in vivo* until approximately age fifteen. By comparing data for teeth and parts of several different bones, information can be gained about human and animal migration during life.

Determination of radioactive isotope ratios in human remains may help determine the post-mortem interval, that is, the time since death. In the case of bodies which are about a year to several decades old, lead and polonium isotopes provide the most useful information, while for longer time periods other isotopes such as caesium and radiocarbon can help to distinguish modern from ‘archaeological’ bone.

Increasingly, the work of forensic geologists is being used not only for intelligence purposes in criminal investigations, but as expert witness evidence presented in court. Geological evidence has provided a significant contribution in recent years to a number of high profile trials involving murder, terrorism, international drug smuggling and people trafficking. Other areas of frequent geological expert witness testimony include various aspects of environmental forensics (e.g. contamination studies), engineering geology failures and traceability studies relating to food-stuffs and raw materials.

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Keywords

Forensic geology, soil evidence, trace evidence, environmental profiling, skeletal remains (dating of), isotopes (stable, radiogenic, radioactive), trace elements, fingerprinting, engineering geology

Table 1. Aspects of sediments and soils which have been used for the purposes of forensic comparison

A. Bulk sample properties	Main techniques / equipment used
Rock/ sediment / soil texture	X-radiography, micro-tomography, optical and scanning electron microscopy, image analysis
particle size distribution	dry and wet sieving, laser granulometry
particle shape properties	image analysis
surface area	nitrogen gas adsorption
colour	Colour charts, spectrophotometry
pH	pH electrode, colourimetry
water soluble cations and anions	atomic absorption, ion chromatography
enzymes	enzymatic extraction and
bacteria	culture experiments, microscopy
lipid biomarkers	gas chromatography mass spectrometry
carbon, nitrogen and sulphur content	wet chemistry, CHNOS elemental analyzer
bulk organic matter content	Walkley-Black colorimetric method, Fourier-transform infra-red spectroscopy, pyrolysis-gas chromatography-mass spectrometry
poly-aromatic hydrocarbons	gas chromatography-mass spectrometry, high pressure liquid chromatography
calcium carbonate content	Collins calcimeter, Chittick apparatus
thermoluminescence characteristics	heat-induced photon emission
fluorescence characteristics	fluorescence microscopy
major and trace element composition	X-ray fluorescence, inductively-coupled plasma spectrometry, neutron activation

bulk mineralogy	optical microscopy / point counting, automated scanning electron microscopy / X-ray chemical microanalysis, X-ray diffraction
clay mineralogy	X-ray diffraction, infra-red spectroscopy
mineral magnetics	magnetic susceptibility, frequency-dependent susceptibility, isothermal remanence magnetization
stable carbon, nitrogen and sulphur isotopes	continuous flow mass spectrometry, laser fluorination mass spectrometry
radiogenic isotopes	thermal ionization mass spectrometry, quadrupole mass-spectrometry, laser ablation mass-spectrometry
radioactive isotopes	alpha-counting, beta- counting, gamma-counting

B. Individual particle type properties and assemblages

opal phytoliths	optical and scanning electron microscopy, supplemented by energy-dispersive X-ray chemical analysis
foraminifera	as above
coccoliths	as above
coralline particles	as above
molluscs	as above
gastropods	as above
ostracods	as above
diatoms	as above
insect remains	as above
pollen and spores	as above

plant seeds	as above
leaf and stem fragments	as above
coal fragments	as above
charcoal fragments	as above
wood fragments	as above
quartz sand grain surface textures	as above
gravel surface textures	as above
coatings on mineral grains	as above
light fraction mineral grains	as above, plus cathodoluminescence microscopy, laser Raman spectroscopy, electron probe analysis, ion probe analysis, laser ablation inductively-coupled plasma spectrometry, micro-spectrophotometry, dating by Ar-Ar and U-Pb series methods
heavy minerals	as above
slag and ash	as above, with exception of dating
spherules	as above
brick	as above
concrete	as above
pottery	as above
glass	as above
alloys and pure metals	as above
fibres	optical microcopy, fluorescence microscopy, micro-spectrophotometry, scanning electron microscopy, X-ray chemical microanalysis, Fourier-transform infra-red spectroscopy and microscopy, ultra-violet spectroscopy
paint	as above
paper	as above

Figure 1. Boots and spade seized from an individual suspected of digging illegal treasure trove from a national heritage site.

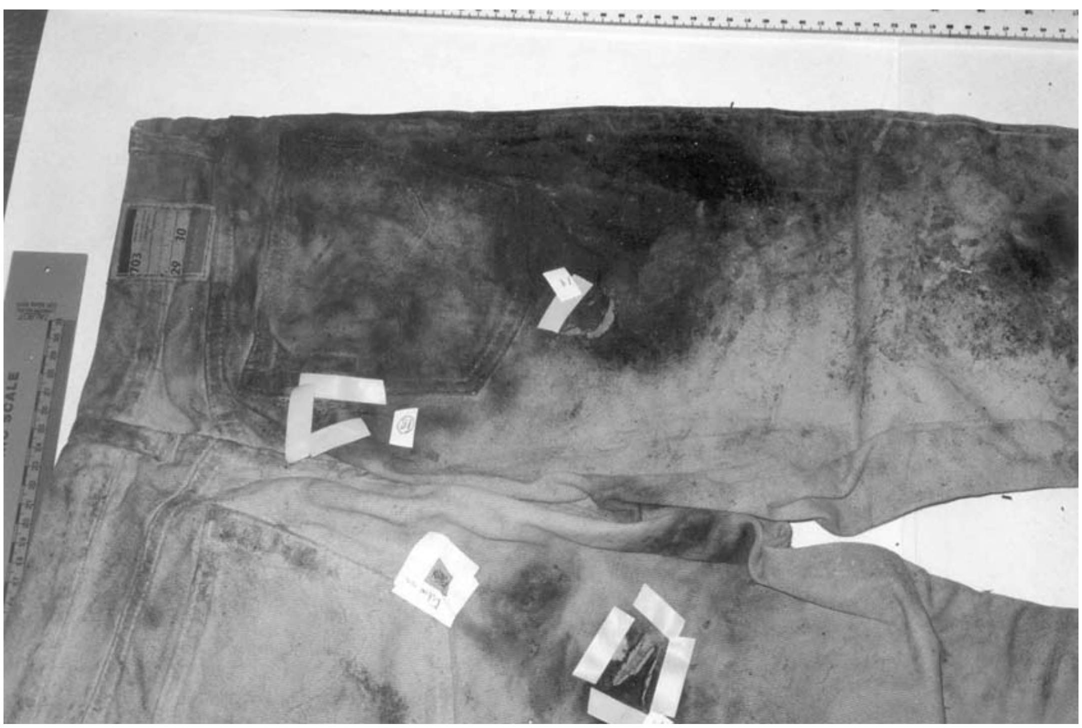

Figure 2. Extensive soil staining on a pair of jeans taken from the victim of a multiple stabbing dumped in woodland.

Figure 3. Mud spots on the jersey of an individual suspected of having buried the body of a murder victim.

Figure 4. A burnt out car used by a man later convicted of having stabbed his wife to death.

Figure 5. House brick with soil staining recovered from a hold-all containing the dismembered remains of a prostitute dumped in a canal.

Figure 6. Soil-stained boot from a deceased male found in the undercarriage stowage space of a Boeing 707.

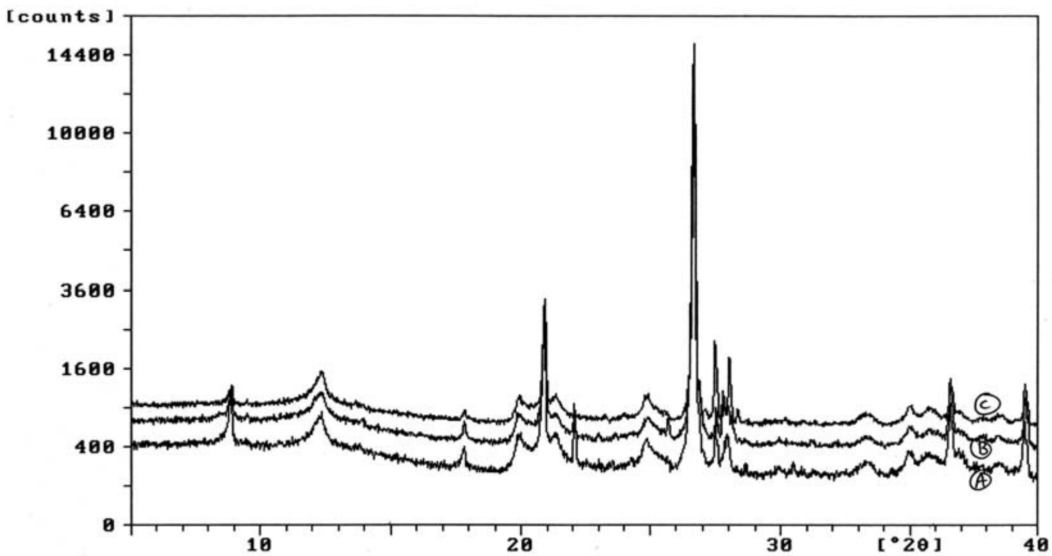

Figure 7. Comparison of X-ray powder diffractograms for the <150 micron fraction of soil samples (A and B) from the right and left boots of a deceased stowaway found in the undercarriage well of a Boeing 747 jet after landing in London, compared with a control sample from Accra airport, Ghana (C).

Figure 8. Example of an 'exotic' synthetic Cr-rich particle identified by optical microscopy, interpreted to be of 'industrial' origin.

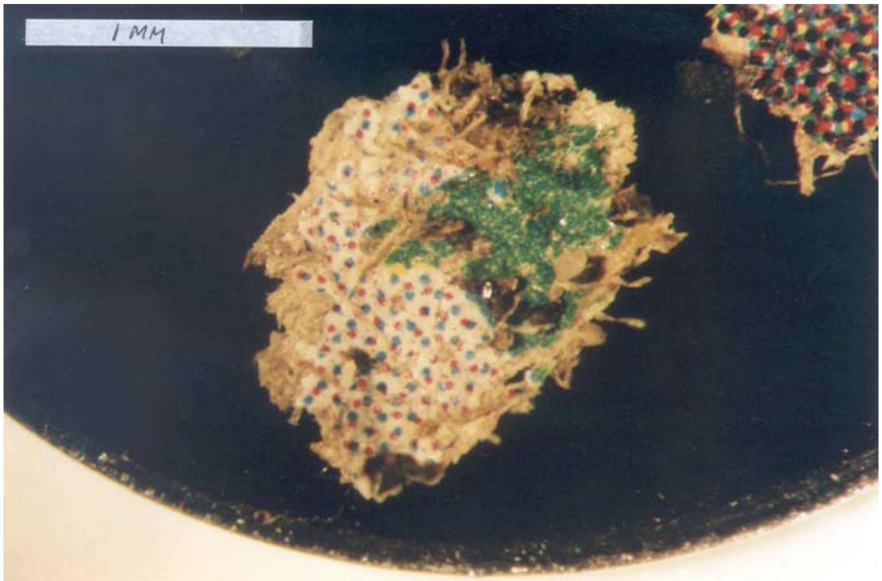

Figure 9. A further example of ‘unusual’ particles found in soil on the boots of a suspect later convicted of murder. The particles are from the cover of a particular issue of a glossy magazine, copies of which had been dumped at the murder scene.

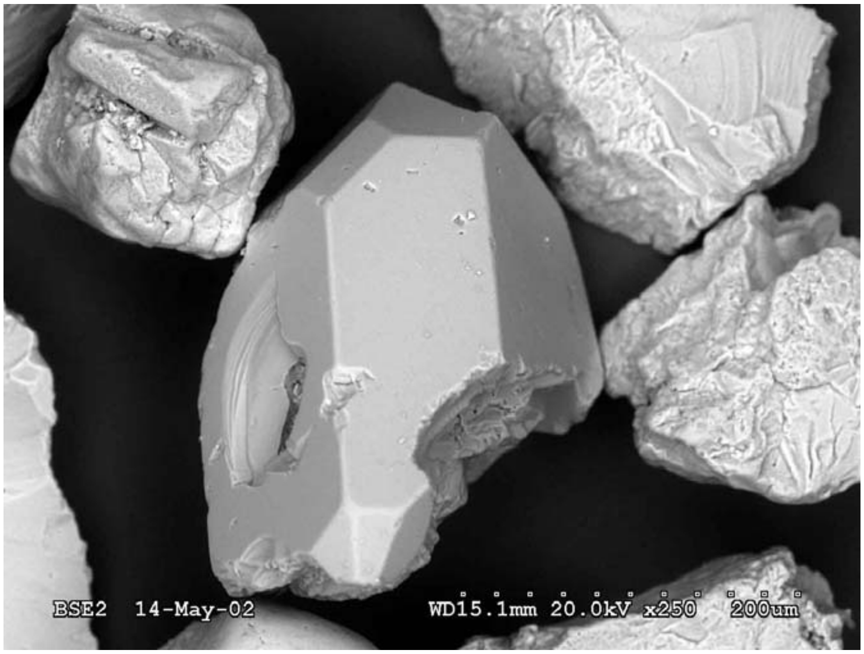

Figure 10. Scanning electron microscope photograph of a very fresh, un-abraded and un-corroded euhedral quartz grain. Such particles are only normally found very close to the rock source.

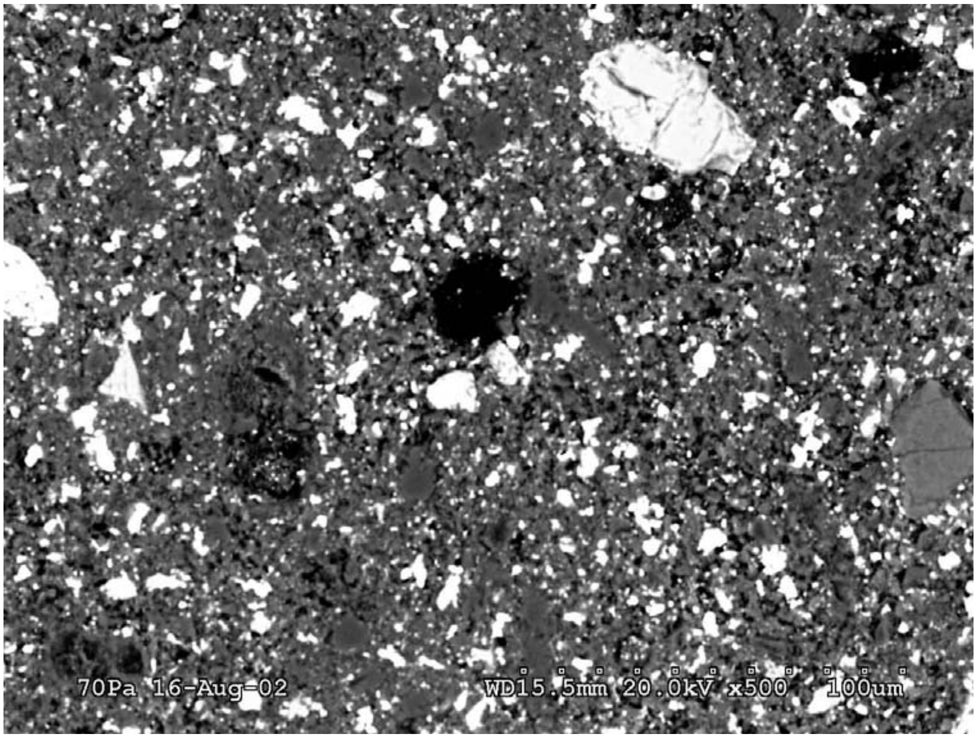

Figure 11. Scanning electron microscope photograph of polished section of a piece of Chalk recovered from the suspension of a car owned by an individual later convicted of murdering two young girls and using the car to deposit their bodies.

Figure 12. Group of 23 gravel-size particles recovered from the trachea and upper bronchii of a murder victim who had been shot in the head and his body set on fire, apparently after having his head immersed in a freshwater stream.

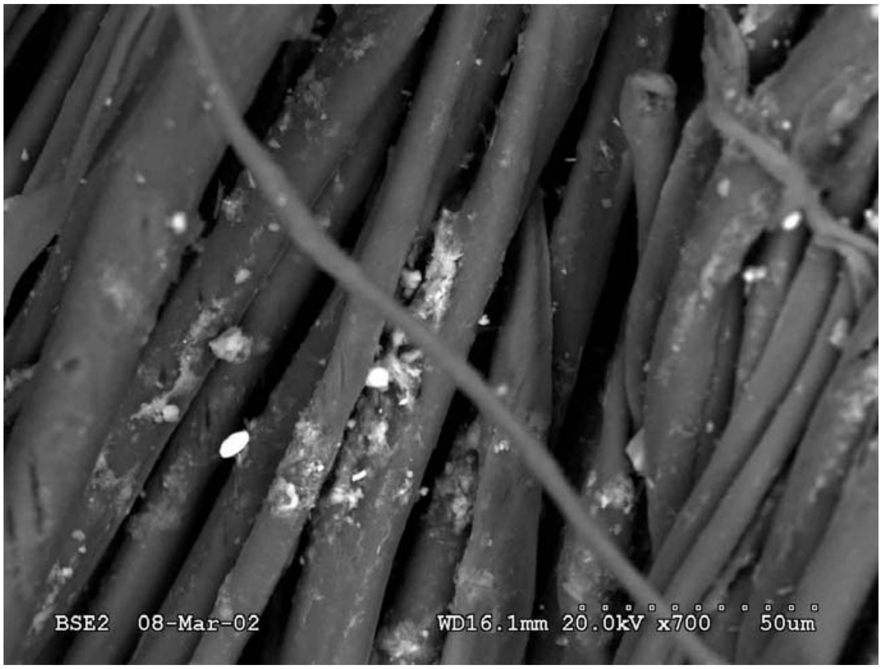

Figure 13. Scanning electron microscope photograph showing sediment particles adhering to fibres in a pair of orange shorts which had been placed on the torso of a murdered child found in the River Thames.

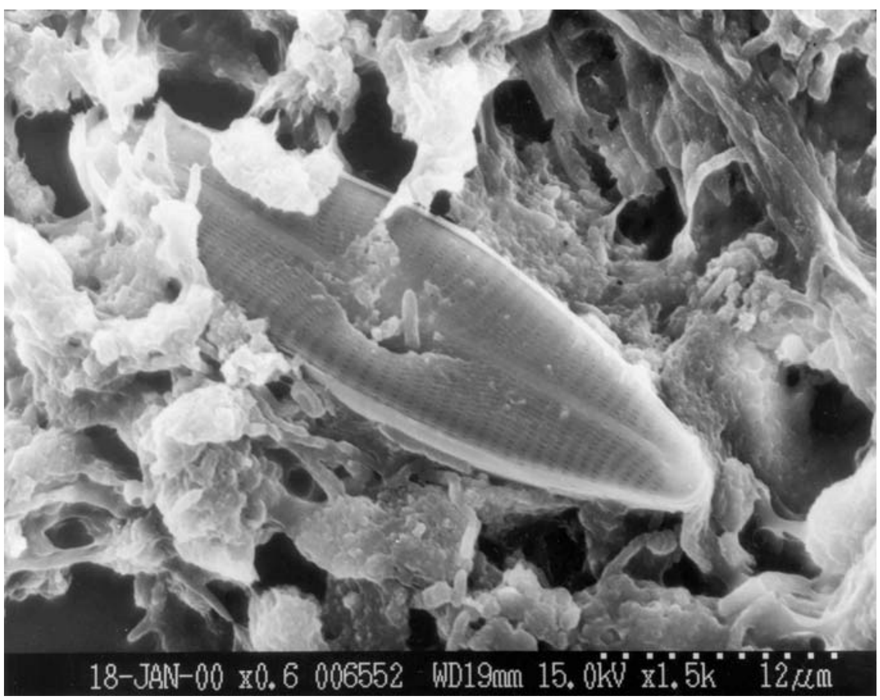

Figure 14. Scanning electron microscope photograph of a pennate diatom found within the lung tissue of a suspected drowning victim.