Chapter 3
Geological Analysis of Soil and Anthropogenic Material. Three Case Studies

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Abstract In a judicial investigation, the evidence provided by pedological materials can have significant evidential value. The forensic geologist is able, in many instances, to obtain compatible results from pedological materials, and anthropogenic fragments in soil, by combining a variety of analytical methods. However, it must be noted that soil trace evidence can be modified during its transfer to an object, and after its deposition. This aspect needs to be considered when processing and interpreting the analytical data. In this paper, three cases are presented which exemplify the use of geological traces and anthropogenic materials in a criminal investigation.

The first case involves damage to a coachbuilder shop where soil samples contained unique anthropogenic fragments frequently used in the automobile industry and manufacturing. The presence of these in soil adhering on the suspects' shoes compared well with the kind of work carried out in such workshops, and what was known about the nature of the crime. This allowed a link to be established between the footwear and the coachbuilder shop where the damage had taken place.

The second case is that of the homicide of a young girl: her burned body was found in the countryside near the town of Misilmeri, in Sicily. Soil found adhering to the roots of *Cyperus alternifolius* (umbrella papyrus) was found at the deposition site even though the plant was not growing there. This soil, and that found on the victim's partially-burned shoes, was very similar to that attached to dried plants in the garden of the suspect's home. The similarity of the soils, the presence of *C. alternifolius* at the suspect's home, and the anomalous presence of the same plant at the deposition site, provided convincing evidence that the suspect had had contact with the place where the girl's body was found.

The last case is the damage of Jewish graves in the Verano Monumental Cemetery in Rome. Tools belonging to a group of gardeners, who had been working illegally in the cemetery, showed traces of white material that could have been transferred from a damaged headstone during impact. Evidence from several independent analytical methods suggested that the gardeners had been involved in the offence.

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These examples suggest how the data can be useful only if they are suitably placed in the context of the investigation. However, for better discrimination for studying soil samples in a judicial investigation, the analysis of the organic fraction of soil (e.g. botanical elements) is essential, especially in those cases where soil samples come from area with homogeneous pedology, or when it is necessary to distinguish the temporal deposition of a soil trace.

3.1 Introduction

In a judicial investigation, the evidence provided by pedological materials, such as samples of soil or sand, can have significant evidential value. Pedological materials include three fractions which have very variable reciprocal ratios: inorganic, organic, and anthropogenic (Lombardi et al. 1983; Murray 2004; Di Maggio et al. 2009; Bergslien 2012). The latter is an assemblage of various materials that have been brought into a soil by human activity. The inorganic fraction is composed of fragments of rock and minerals and, where the landscape geology is relatively homogeneous, the mineralogy can be very similar over large areas. In such cases, the organic and anthropogenic fractions greatly facilitate identification of the location and origin of a soil.

The organic fraction may include living plant roots, algae, protists and animals, as well as functioning microbial communities. After death, organisms become decomposed to fragments, and are eventually converted into humus, and a complex of humic acids. Thus, the organic fraction is represented at both molecular and particulate levels, and its quantity and quality reflects both the regional and micro-environmental factors prevailing during pedogenesis. The anthropogenic fraction can include fragments of various materials (e.g. paper, glass, plastic, fibres, paint, metal, bricks, baked clay, cements), and chemical substances such as precipitates, solvents, general scoria (Di Maggio et al. 2009). These materials can provide valuable trace evidence to link a soil to its place or origin.

There is little doubt that excellent results can be achieved with this kind of micro-trace evidence when the information is correctly viewed within the context of the criminal investigation. The forensic geologist is able, in many instances, to obtain compatible results from pedological and anthropogenic materials by combining a variety of analytical methods (Murray 2004; Pye 2007; Ruffell and McKinley 2008). However, it must be noted that, like any other type of evidence, soil traces can be modified during and after transfer to an object. In this case, the inherent nature of the pedological material, meteorological conditions before the collection, and the force and direction of energy involved in transfer and deposition, are all factors to be considered when processing and interpreting the analytical data (Di Maggio et al. 2009).

After deposition onto an object, soil particles can disperse or be lost, and new material(s) may be added. Newly added material may be deposited on top of, or mixed with, the original trace material. Furthermore, surfaces and fabrics can vary in their ability to retain trace evidence, so transference will involve an element of selectivity. This can be a function of clast size and/or mass. Dispersion, or loss of particles after transference, also affects the degree of comparison possible with a reference sample. For example, losses from the wheel of a vehicle are correlated with the distance of journeys, and the speed of wheel revolution. Mixing is an important consideration in the temporal aspects of deposition. A soil can accumulate on a shoe, or on a vehicle's foot well mat, both before and after soil from the crime scene has been transferred to the item. The crime scene soil can, therefore, be "sandwiched" between other deposits which are not of interest to the investigator.

With repeated use, and absence of cleaning, there is sequential deposition of trace evidence into a car foot well from footwear. Very few mineralogical species can reflect season or weather (Lombardi et al. 1983), and this obviously imposes limitation on the interpretation of mineralogical data. Thus, from the minerogenic component alone, it may be difficult to distinguish even the most recently deposited material from that originally accumulated at the time of an offence. However, because of the predictability of flowering and sporing times, analysis of plant macro-remains, plant spores, pollen and fungal spores, might give more information on temporal aspects of deposition.

Three cases are presented here which exemplifies the use of pedological and anthropogenic material in criminal investigation.

3.2 Case 1: The Damage to a Coachbuilder Shop

Early one morning in 2010, both the interior and exterior of a coachbuilder's shop was damaged. Windows were broken, and some of the machines inside the workshop had been severely damaged. The identity of the perpetrators of the damage was unknown. However, some days before the incident, the owner of the shop had been offered protection from harm to his property in exchange for money. Thus, the inquiry became one of extortion. A few days later, police identified two suspects who already had a criminal record of extortion, and shoes which had traces of soil were seized from them.

The scene of crime was a front yard, adjacent to the shop, and this was surveyed by the police. There was a large area of bare, exposed, moist soil littered with small fragments, possibly of paint and glass. There were tyre tracks and footprints in the soil of the yard and it was obvious that vehicles were often parked there. The tyre impressions and footprints were poorly preserved, and not suitable for comparison with existing manufacturer databases, but the police collected soil samples for investigation by a forensic geologist.

3.2.1 Aims

The aim of the analyses was to establish whether there was a link between the footwear and the yard soil. A high degree of similarity between the two soils might indicate contact between the footwear and the yard.

3.2.2 Methods

The forensic geologist collected five samples of soil from the front yard adjacent to the shop. Fresh tire and footprints were targeted. The soils over the yard were relatively homogeneous so, for simplicity, only one sample is reported here (designated YARD). A soil sample was also collected from each of the suspects' footwear (designated SHOE 1 and SHOE 2).

Soil samples were dried at 60 °C, weighed into tubes, and disaggregated in an ultrasonic bath. These were wet-sieved with sieve mesh sizes spaced at one-phi intervals between 2000 and 4 μm. Samples were viewed with stereo-binocular microscope (within a range of 10x-50x), and colour of clay fractions assessed with Munsell Colour Charts (Macbeth 2000). Samples were embedded in resin, and thin sections of the sand particles were examined by polarizing light microscopy. To determine the volume fraction percentage of identifiable constituents in the thin sections, semi-quantitative analysis was carried out by point counting and size measurement. This was performed using a manual, mechanical stage with mm-graduated x-y stage translation controls for moving the thin section.

The whole of each soil sample was subjected to X-ray diffraction (XRD analysis) by means of a Philips PW 1800 diffractometer, with radiation Cu-Kα generated at 40 kV and 40 mA. Each of the XRD analysis charts was drawn within an angular value range of 5–80°, at a step size of 0.01, and at a time per step of 0.9 s.

The anthropogenic fragments in the soils were subjected to the non-destructive techniques of stereoscopic microscopy and Raman spectroscopy. Raman analysis was by a Horiba LabRAM Aramis. Each of the Raman analyses were carried out within the following instrumental conditions: laser wavelengths 785 nm, objective 10× with a working distance of 0,38 mm, hole 200 μm, 600 I/mm grating, and slit 200 μm.

There is extensive literature dealing with examination of materials such as paint and glass, using Raman spectroscopy (e.g. Long 2002; Edwards 2004) and X-ray diffraction (e.g. Kugler 2003). However useful overviews of these techniques applied to anthropogenic materials in a forensic investigation are provided by Claybourn (2004), and Ruffell and Wiltshire (2004). These suggest how data can be useful only if they are suitably placed in the context of the investigation.

3.2.3 Results

The detailed examination by stereoscopic observation and Raman spectroscopy revealed that they all contained particles of anthropogenically-derived hyaline microspheres, blue fragments, and white fragments embedding hyaline microspheres.

Soil The soil samples were very pale brown (10YR 8/2). Stereoscopic microscopy revealed that all the soil samples had particles of very similar morphology. They were irregularly shaped, ranging from angled to sub-angled. X-ray diffraction showed all the samples consisted of the same crystalline phases, namely quartz, plagioclase and calcite (Fig. 3.1). Thin section observations by polarizing light microscopy revealed that all the soil samples had the same suites of minerals (quartz, plagioclase, calcite, serpentine, biotite, and magnetite), and rock fragments (sandstone, limestone, flints, quartzites, phyllites, and micaschists).

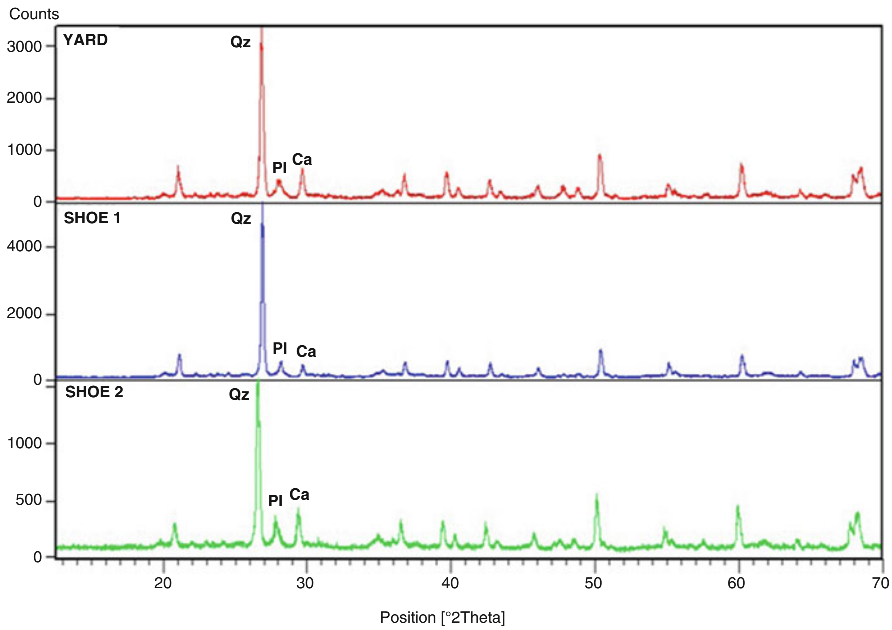

Fig. 3.1 X-ray diffractograms of soil samples SHOE1, SHOE2, and YARD. The comparison among all the spectra shows the similarity between the soil samples. The critical peaks are labelled with the initials of minerals. *Ca* calcite, *Pl* plagioclase, *Qz* quartz

Table 3.1 Values of the relative percentages of sialic and femic minerals, and sedimentary and metamorphic rocks in the samples SHOE1, SHOE2, and YARD

Sample	SHOE 1	SHOE 2	YARD
Sialic minerals	11.5	12.0	10.2
Femic minerals	4.9	4.3	5.0
Sedimentary rock	69.2	67.3	68.2
Metamorphic rock	14.0	16.4	16.6
	100	100	100

A semi-quantitative analysis was performed to estimate the abundance of sialic[1] and femic[2] minerals, and sedimentary and metamorphic rock, in both the yard comparator samples and those from the footwear. The relative percentages are shown in Table 3.1.

There was little difference in the results of grain size analysis between the footwear and that of the crime scene soil, although soil from both shoes showed a greater abundance of the fine fractions. Grain size was, therefore, of little probative value and this emphasised the importance of the anthropogenic materials.

Hyaline Microspheres The hyaline microspheres had dimension between 250 and 500 μm (Fig. 3.2a, b). Raman spectroscopy showed that these spheres were common glass (Fig. 3.3a).

Blue Fragments The blue fragments were between 100 and 500 μm (Fig. 3.2c, d). Raman spectroscopy showed that they consisted of a pigment called Hostaperm blue (Fig. 3.3b).

White Fragments Embedding Hyaline Microspheres The white fragments embedding the hyaline microspheres were between 50 μm 100 μm (Fig. 3.2e, f). Raman spectroscopy revealed that the white material to be of anatase and rutile (Fig. 3.3c), and the microspheres were of common glass.

3.2.4 Discussion and Conclusion

The various analyses demonstrated that both the comparator soil from the yard, and from the suspects' shoes were similar with respect to colour, grain morphology, mineralogy, and petrography. There was a slightly greater abundance of the finer soil fraction in the shoe samples than the yard sample. This could be a function of clast size in that the coarser fraction is probably more easily lost during wear.

[1] The assemblage of minerals, rich in silica and alumina, that comprise the continental portions of the upper layer of the earth's crust.

[2] Minerals having one or more normative, dark-colored iron, magnesium, or calcium-rich as the major components of the norm.

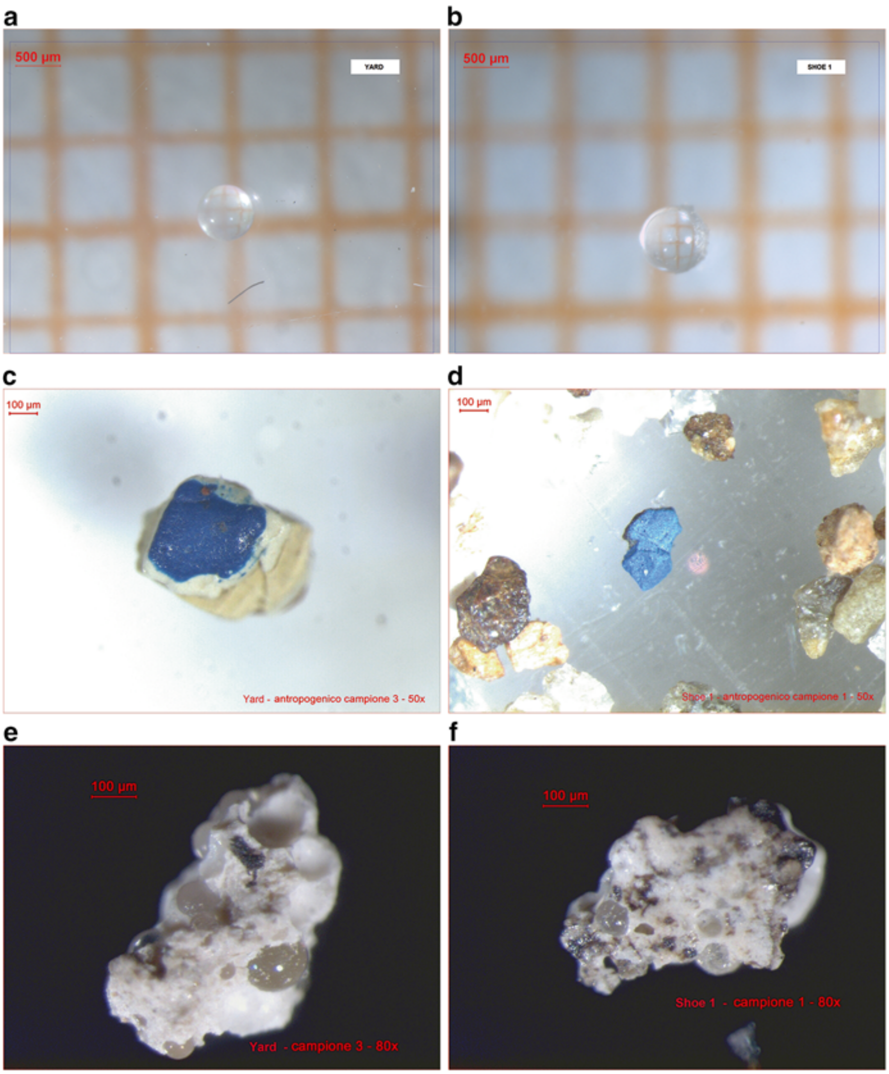

Fig. 3.2 Anthropogenic fragments in the soil samples: (**a**) hyaline microsphere in sample YARD; (**b**) hyaline microsphere in sample SHOE1; (**c**) blue fragment in sample YARD; (**d**) blue fragment in sample SHOE1; (**e**) white material embedding hyaline microspheres in sample YARD; (**f**) white material embedding hyaline microspheres in sample SHOE1

However, the three kinds of anthropogenic fragments found in all the soils were more informative. Raman analysis revealed that the three kinds of material in all the soil samples had the same nature: glass microspheres, blue fragments of pigment, and a white material, consisting of anatase and rutile, which had glass microspheres embedded within it.

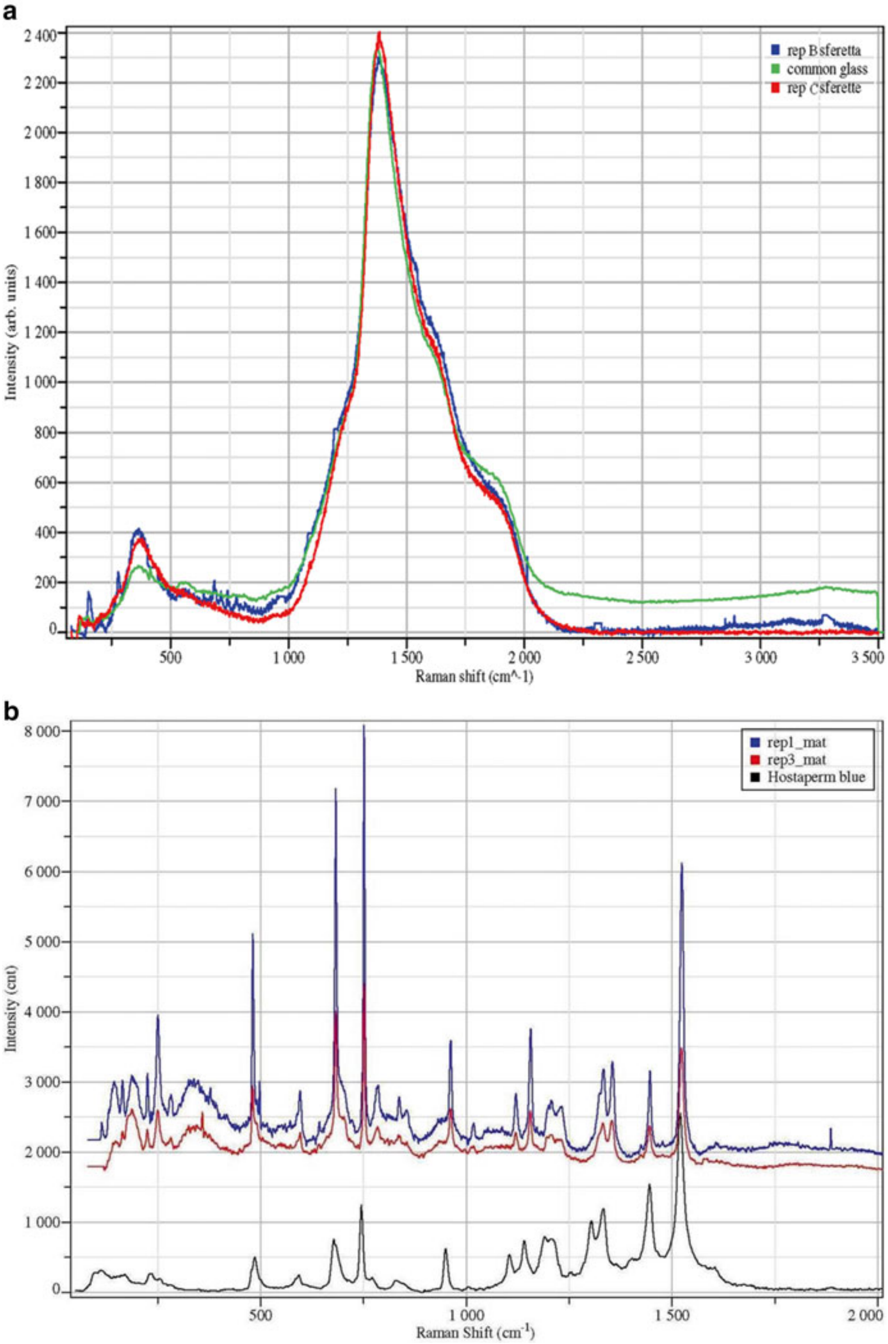

Fig. 3.3 (**a**) Raman spectra of hyaline microspheres: in blue the spectrum of microsphere in sample SHOE2, in red the spectrum of microsphere in sample YARD, in green the database spectrum of common glass; (**b**) Raman spectra of blue fragments: in blue the spectrum of fragment in sample SHOE1, in red the spectrum of fragment in sample YARD, in black the database spectrum of Hostaperm blue pigment; (**c**) Raman spectrum of white fragment embedding hyaline microspheres (*blue line*); in green and red the database spectra of anatase and rutile

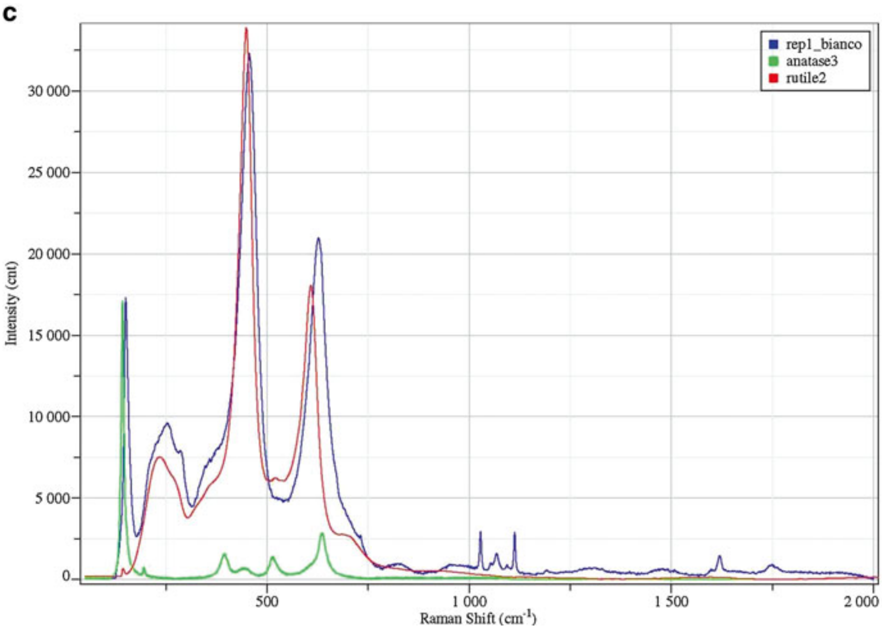

Fig. 3.3 (continued)

Glass microspheres were probably derived from shot peening, which although used in various industrial processes, is also used for cleaning and polishing metal gearings, and in treating metal bodywork. The dimension of the spheres used in the process depends on the level of finishing required.

The blue Hostasperm pigment is used in the manufacture of high performance paints for application to metal, resin, and PVC. Its quality of high resistance makes it suitable for the automobile industry.

Rutile and anatase are frequently used for the production of paints. Paints embedding glassy microspheres are called A-way paints; they have reflective properties and are used for painted road signs.

These three materials are not ubiquitous, and are likely to be found only in an environment associated with specific activities such as those carried out in the damaged workshop. Although the gross soil characteristics were less helpful in identifying a specific link between the footwear and the soil of the yard, the anthropogenic fragments added a high level of specificity. They related to the trade carried out at the crime scene, and their presence in the shoe soil samples indicated contact between the yard and the suspects' footwear.

3.3 Case 2: The Homicide of Nike Adekunle

In 2012, the murdered, semi-burned body of Nike Adekunle, a Nigerian prostitute, was found in the northern Sicilian countryside, near the village of Misilmeri. It was the latest in a series of crimes in which Nigerian prostitutes were involved and, early in the investigation, police addressed their enquiries to members of criminal organisations known to manage prostitution between Africa and Italy. However, a few days after the body had been found, they turned their attention to a man who, according to witnesses, had been the girl's last customer.

During the *post mortem* examination traces of soil were found on the victim's shoes and, when the deposition site was being evaluated by the police and forensic geologist, dried plant roots with some associated soil were noted and collected. The roots were identified by a botanist to be of *Cyperus alternifolius*. It is grown as an ornamental around the world, and its presence at the deposition site was considered anomalous since there was no evidence of the plant growing anywhere in the environment of the place where the body was found. The geologist subsequently visited the suspect's home and collected soil samples from inside and outside his garden. During this visit, dried roots, as well as a stack of dried and fresh plants of *C. alternifolius*, were found in the backyard.

From this information, investigators postulated that the suspect had killed the girl in his home, put her body into his off-road vehicle, and then covered it with some of the dried plant remains of *C. alternifolius* from his garden. He then drove a distance of 5 km, dumped the body, and burned it with petrol.

3.3.1 Aims

The aims were: (a) to compare soil from the victim's shoes with that from the suspect's home to ascertain the likelihood of common origin, (b) to compare soil adhering to the plant root material found at the deposition site with that from the suspect's garden to establish that they were associated, and to show that the roots were not derived from the deposition site itself.

3.3.2 Methods

At the suspect's home, the geologist collected soil samples from inside and outside the garden. This was considered necessary in order to ascertain whether or not the garden offered a unique pedological microenvironment. If this were the case, its soil could be specifically distinguished from that of other locations. Eight soil samples were collected to ascertain their spatial heterogeneity within the garden. The soil proved to be remarkably homogeneous so, for brevity, only one of the garden samples is presented (designated HOME). The soils adhering to the plant roots found at the deposition site, and from the suspect's home are designated P1 and P2. The soil from the victim's shoes and the deposition site are designated SHOE and SITE respectively.

The protocols and methods used in this case were the same as those described in Case 1. Each of the XRD analysis charts were drawn within an angular value range of 3–80°, at a step size of 0.01, and at a time per step of 1 s.

The anthropogenic fragments in soil were subjected to stereoscopic microscopy and FT-IR spectroscopy (Fourier Transform Infrared Spectroscopy) (Griffiths and De Haseth 2007). FT-IR analysis involved using a Thermo Scientific Nicolet iS 50 FT-IR spectrometer, with a laser wavelength of 780 nm. A useful overview of this technique applied to anthropogenic materials in a forensic investigation is provided by Beauchaine et al (1988).

The dried root material was identified by a botanist, using fresh material collected from the suspect's home as reference material.

3.3.3 Results

There were three components to the scientific examination: (a) identification of the plant material (b) analysis of red fragments of anthropogenically-derived material, and (c) analysis of gross soil characteristics.

Dried Plant Material The plant proved to be *Cyperus alternifolius*. It has several common names including "umbrella papyrus, umbrella sedge, and umbrella palm".

Red Fragments The soil on the root material from the deposition site and the suspect's garden contained the same dark red fragments (Fig. 3.4a, b). The FT-IR charts showed very similar spectra for the red fragments in soil samples P1 and P2, suggesting they were made from the same materials (Fig. 3.5a). Comparison with appropriate databases indicated that these were anthropogenically-derived, and likely to consist of clay coating and alchydic paint (Fig. 3.5b).

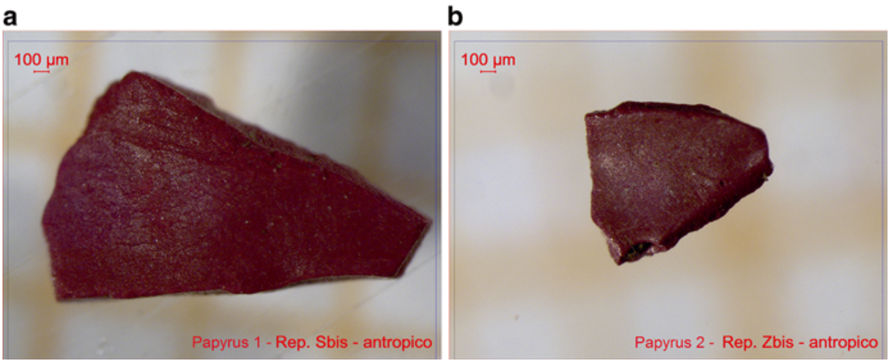

Fig. 3.4 Anthropogenic fragments in the soil samples from the roots of papyrus: (**a**) red fragment in sample P1; (**b**) red fragment in sample P2

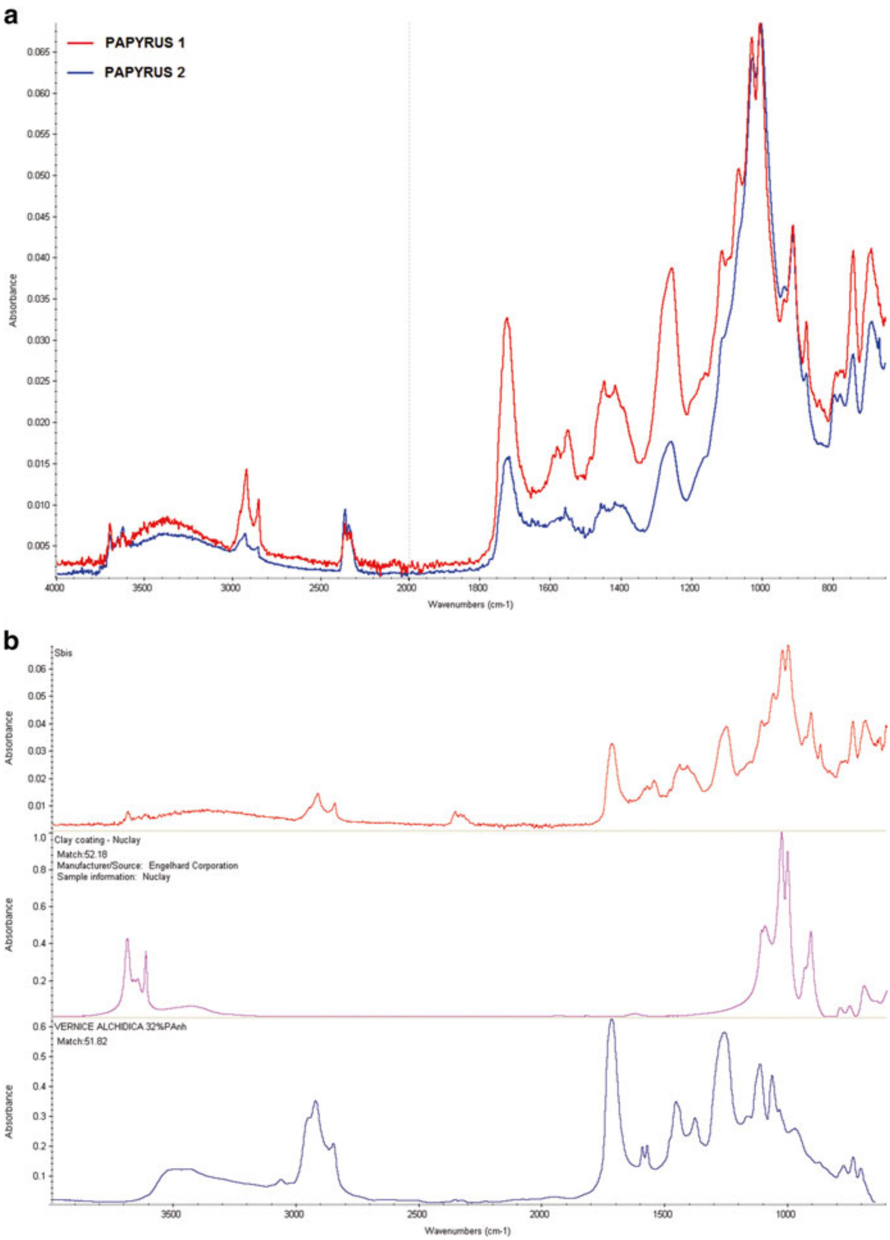

Fig. 3.5 FT-IR spectra: (**a**) red fragments found in sample P1 (*red line*) and P2 (*blue line*); (**b**) comparison between the database FT-IR spectra of clay coating and alchydic paint

Soil Stereoscopic microscopy showed that in all samples, soil grains were similar in typology and shape (from sub-angled to sub-rounded). With regard to colour, the soil on all the exhibits (P1, P2, SHOE, HOME) was light reddish brown (2,5YR 6/4) while that from the deposition site (SITE) was pink (5YR 7/4). The colour and grain size distributions were similar for all the soils except for that from the deposition site.

X-ray diffraction of the deposition site soil showed that its mineralogy was dominated by calcite, dolomite, kaolinite, and quartz. However, although the soil mineralogy of the plant roots, the victim' shoes, and the suspect's garden also contained dolomite, kaolinite, and quartz, it was notable that calcite was absent.

Observation of thin sections under polarized light confirmed that, with respect to mineralogy and petrology, the deposition site soil was different from all the others. It contained the minerals calcite, quartz, and magnetite, and rock fragments of quartz-arenite, lithic arenite, quartzites, limestone, and organogenic limestone. The soil from the garden, shoe, and plant roots had the minerals quartz, dolomite, sanidine, and magnetite, while the rock fragments were of quartz-arenite, quartzites, limestone, and micaschists (Table 3.2).

A semi-quantitative analysis of the abundance of sialic minerals, sedimentary rocks, and metamorphic rock in all the samples was also performed. The relative percentages are shown in Table 3.3.

Table 3.2 Minerals and rock fragments in the samples SITE, HOME, SHOE, P1, and P2

Sample	SITE	HOME	SHOE	P1	P2
Calcite	+	–	–	–	–
Lithic arenite	+	–	–	–	–
Organogenic lim	+	–	–	–	–
Dolomite	–	+	+	+	+
Sanidine	–	+	+	+	+
Micaschists	–	+	+	+	+
Magnetite	+	+	+	+	+
Quartz-arenite	+	+	+	+	+
Limestone	+	+	+	+	+
Quartzites	+	+	+	+	+
Quartz	+	+	+	+	+

Table 3.3 Values of the relative percentages of sialic minerals, and sedimentary and metamorphic rocks in the samples SITE, HOME, SHOE, P1, and P2

Sample	SITE	HOME	SHOE	P1	P2
Sialic minerals	25.3	20.5	19.9	17.2	17.4
Sedimentary rock	57.8	72.2	72.9	71.0	70.3
Metamorphic rock	16.9	7.3	7.2	11.8	12.3
	100	100	100	100	100

3.3.4 Discussion and Conclusion

The various analyses demonstrated that, in terms of colour, grain size distribution and morphology, mineralogy, and petrology, the soil from the exhibits (HOME, SHOE, P1, P2) were similar enough to indicate a common provenance. However, the profiles showed an accentuated similarity between the samples HOME and SHOE, and between P1 and P2 (the plant roots). This can be accounted for by the soil from the garden and the shoe having been from the surface, while that from the plant roots would have been from a deeper soil profile (10–15 cm deeper). Physico-chemical characteristics of soils can differ both laterally and vertically over small distances, and this is emphasized by the contrast between the soil from the exhibits and that from the deposition site.

The high level of similarity between the soil from the garden and the victim's shoe suggests that little, if any, loss of original soil, or accumulation of new material, had occurred. This might indicate that the girl's feet had not contacted the ground outside the suspect's garden or, indeed, at the deposition site. The presence of the clay coating and alchydic paint fragments (possibly derived from building materials such as roofing tiles) in the garden soil, and in the detached roots of *C. alternifolius* at the deposition site, suggests a link between the two places. The absence of the red fragments in the deposition soil itself indicates that the garden had been the source.

The plant roots themselves were of considerable importance to this case in that *Cyperus alternifolius* is not native to northern Sicily. It requires cultivation and does not spread as an adventive. Its presence at the deposition site and in the garden of the accused, provided significant, additional evidence of a link between the suspect and the place where the girl's body was found.

The geological findings corroborated the police's hypothesis outlined above

3.4 Case 3: Damage to Jewish Tombs

The day before a Jewish religious celebration, Jewish tombs in the Verano Monumental Cemetery in Rome were severely damaged. Headstones, made from limestone marls and travertine, had been broken, and some graves had been opened (Di Maggio and Nuccetelli 2013).

Police investigators suspected that a group of gardeners, who were doing illegal gardening and repair work in the cemetery, might be involved. The Police carried out a judicial site survey of the scene of crime, and seized gardening equipment which they found in a box inside the cemetery. This box belonged to the gardeners under investigation and the tools included picks and iron bars.

The gardeners claimed they had used these tools to restore some partition walls in the graveyard with white mortar few days before the damage. The walls were unrefined and made from tufaceous bricks, with dark mortar filling the gaps; some gaps had been roughly filled with easily removable, and brittle, white material.

3.4.1 Aims

The aims of the investigation were to compare samples of trace marks on the tools with material from the damaged headstones and white material from the walls. If the results of inorganic analyses showed a greater concordance between the marks on the tools and the headstones than to material from the wall, the testimony of the workmen could be challenged.

3.4.2 Methods

The grave headstones were constructed either of travertine or of limestone marl. Samples were taken from them in areas of fresh breaks in the stone since these probably represented the points of impact with the tools. White material from the partition walls was also taken for comparison with the small marks on the tools. Because of the small amount of material on the pick and bar, sampling was carried out very carefully to maximise retrieval.

Non-destructive techniques were used for analysis of all the samples. These were stereoscopic microscopy, X-ray diffraction (XRD), and elemental study with SEM-EDX (Pye 2004). Each of the XRD analysis charts were drawn within an angular value range of 5–80°, at a step size of 0.01 and at a time per step of 0.5 s. SEM-EDX analysis involved using a Tescan Vega microscope, at variable pressure, and EDAX microanalysis. Each of the EDX analysis charts were done by counting 100s.

There is extensive literature on the use of SEM-EDX and XRD in examining rock material, and industrial products such as bricks and concrete (Pye and Krinsley 1984; Allen et al. 2000; Evans and Tokar 2000; Schiavon 2002).

3.4.3 Results

The detailed stereoscopic microscopic examination of the white marks on the tools revealed that they were doughy and compact, but easily removed. They also featured micrometric stripes on the surface. The position of the marks, and orientation of the stripes, on the pick and bar were consistent with an up and down movement of the tools.

Headstones The headstones made from limestone marl gave diffraction patterns typical of pure calcite. The only other peak identified was attributed to a small quantity of quartz. The headstone made from travertine consisted of calcite (Fig. 3.6). Quantitative analysis showed the elements in this headstone were dominated by calcium with smaller quantities of aluminium and silicon (Table 3.4).

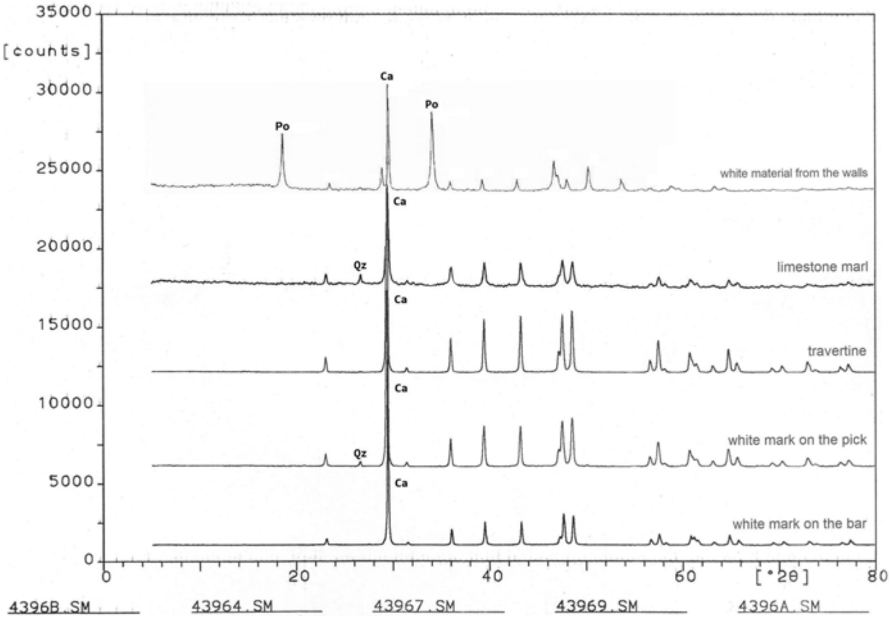

Fig. 3.6 X-ray diffractograms of headstones (limestone marl and travertine), marks on the pick and the bar, and white material from the walls. The critical peaks are labelled with the initials of minerals. *Ca* calcite, *Po* portlandite, *Qz* quartz

Table 3.4 Values of the percentages of calcium, silicon and aluminium in the samples LIMESTONE, PICK, TRAVERTINE, BAR, and WALL

Sample	LIMESTONE	PICK	TRAVERTINE	BAR	WALL
Ca	87.0	88.2	93.7	92.9	100
Si	9.4	8.3	3.9	4.0	–
Al	3.5	3.4	2.3	3.1	–
	99.9	99.9	99.9	100	100

Pick and Bar The pick gave similar results to those of the limestone marl headstones in that calcite and small quantity of quartz were present. The marks on the bar consisted of the same crystalline phase as that of the travertine gravestone, namely calcite (Fig. 3.6). The quantitative data suggested a similarity between the travertine and the mark on the bar, while the limestone marl signature was similar to that on the pick (Table 3.4).

Wall Quantitative analysis showed that the major element in the white wall material was calcium (Table 3.4), while further SEM analysis (at a magnification of 8.00 K X) revealed well-formed hexagonal plates of about 10 µm. These corresponded to portlandite, a calcium hydroxide, which is the major bonding agent in cement and concrete (Fig. 3.6). Portlandite ($Ca(OH)_2$) is formed during the hydration of lime (CaO) and reaction with atmospheric CO_2 to form calcite (carbonation).

Wall mortar should normally contain quartz and/or other minerals as inert material, but none of these was found. The XRD data suggested that the white wall material could be an hydrated lime paste. The diffraction pattern showed close intensities of the peaks of calcite and portlandite. The dimensions of portlandite crystals were compatible with a hydrated lime paste of about 3 months old (Colantuono et al. 2011; Callebaut et al. 2000). Even if the carbonation process was slow, and the sample fresh, it has been shown that in some lime deposits, the ratio of portlandite to calcite is low (Hughes and Swann (1998).

3.4.4 Discussion and Conclusion

XRD analysis showed the material from the walls was different from the white marks on the tools. Furthermore, the peaks of calcite had similar intensities in headstone samples and in the marks, while the peak of calcite in the white material from the wall did not fully correspond with those of the headstone or the marks.

The quantitative data suggested a similarity between the travertine and the mark on the bar, and between the limestone marl and the mark on the pick. The silicon and the aluminum in the limestone marl linked up with the presence of small quantities of quartz and aluminum silicate hydrate. The presence of small quantities of silicon and aluminum in the travertine were consistent with the inclusion of impurities during its genesis. The material from the partition walls consisted of calcium, but no aluminium and/or silicon were found. The total absence of these elements in this sample, as supported the XRD data, suggested again that the material from the wall could be a hydrated lime. Furthermore, the dimension of the well-formed hexagonal crystals of portlandite suggested the hydrated lime paste had been used about three months before. This time did not correspond with the gardeners' claim.

The SEM-EDX data provided further evidence of the similarity of the gravestone with the marks on the tools and the difference of those with the material from the wall. The analysis of the material from the walls revealed that it was not a conventional mortar but, more likely, an hydrate lime paste (made from portlandite and calcite), which had been improperly used to restore the partition walls. Indeed the mineralogical and chemical data did not show the presence of sand or pozzolana which are invariably used as inert material in mortar. However, analysis using stereo-microscopy, X-ray diffraction, and SEM-EDX showed that, although the white material from the walls was different, the headstones contained the same minerals and elements as the marks on the tools.

These combined results suggested that the white marks on the tools were derived from the damaged headstones rather than the hydrated lime of the wall mortar.

3.5 Final Remarks

The three case studies illustrated in this paper showed that the successful application of geology in forensic analysis depends on several factors: (a) obtaining all pertinent samples early in the investigation, (b) accurate interpretation of events at a crime scene, (c) accurate contextualization of information and evidence in the specific investigation, the crime, and its dynamics, (d) the application of techniques suitable for analysis of micro-traces, and (e) appropriate data analysis. The practitioner should also be aware that trace evidence can be modified before and after collection.

It must be noted that analysis of the inorganic fraction alone may fail to discriminate between soils at a degree of resolution that would satisfy the requirements of a case. This is because in any given area, minerals and rocks can be ubiquitous, or certainly very widespread. However, if analysis of anthropogenic inclusions, and organic particulates, such as pollen and spores, is included, there can be a higher degree of resolution in establishing provenance. This is because although spatially large areas may yield similar pedological and geological characteristics, plant communities, and the by-products of human activity are more confined and can, thus, confer specificity.

Forensic geology can be most effective in a criminal investigation when the geologist is regarded as part of the investigative team early in the case. If the geologist is given appropriate information on the case history, and on the dynamics of the crime, sampling can become effectively targeted to maximise the retrieval of critical evidence.

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