DOI: 10.1478/AAPP.101S1A2

AAPP | Atti della Accademia Peloritana dei Pericolanti
Classe di Scienze Fisiche, Matematiche e Naturali
ISSN 1825-1242

Vol. 101, No. S1, A2 (2023)

UNRAVELING CRIMES WITH GEOSCIENCES

Roberta Somma [ab*]

Abstract. The Forensic Sciences play an important and unique role in the Justice System, a role that refers to the expert's ability to provide accurate and objective information reflecting facts and events that occurred during the happening of a crime. These sciences include Criminology and Criminalistics. Forensic Geology is a discipline, 150 years old, applied to criminalistics. It applies scientific principles of Earth Sciences to solve criminal cases. Main activities carried out by forensic geologists concern sedimentological, palaeontological, mineralogical, petrographic, and geochemical analyses, geophysical surveys, and remote sensing inspections. These investigations are used for solving crimes, such as homicides, corpse concealments, kidnappings, hit and run incidents, sexual assaults, counterterrorism, animal maltreating and wildlife crimes, robberies, thefts in apartments, vandalism, stone-throwings, frauds and financial crimes, and environmental damages. The present research illustrated the main activities carried out in Forensic Geology and selected some international and national cases carried out in the last 150 years by forensic geologists, for providing an overview of the scientific approaches, methods, and potentialities.

1. Introduction

The Sciences may play an important and unique role in the Justice System, a role that refers to the expert's ability to provide accurate and objective information reflecting facts and events that occurred in the past during the happening of a crime or a suspect event. The sciences applied for solving criminal cases are best known as Forensic Sciences (Picozzi and Intini 2009; Saferstein 2017). The approach used in Forensic Science investigation is "holistic", being multidisciplinary and transdisciplinary. It is based on the involvement of both criminology (the study of immaterial traces such the criminal thinking) and criminalistics (the study of material traces such the physical evidence of crime scene). Main criminalistic disciplines are: forensic medicine, pathology, toxicology, serology, anthropology, archaeology, entomology, dentistry, biology, chemistry, physics, computer science, and geology (Picozzi and Intini 2009; Saferstein 2017). Forensic Sciences use scientific and technological methods for carrying out activities aimed at identifying the perpetrator of a crime through the analysis of the crime scenes or sites with investigative interest and the related evidence. Associating or excluding a suspect to or from a victim/crime scene is possible by applying the Locard's Principle of exchange on the base of criminalistics

(Picozzi and Intini 2009; Saferstein 2017). The principle states that when two items/bodies interact, an inevitable contact is produced between them which necessarily generates a trace transfer. In criminal cases, there will be an interchange or transfer of material traces and micro traces between suspect, victim, and crime scene (Locard's trilogy, Figure 1).

FIGURE 1. In criminalistics, the Locard's trilogy expects that for each crime there must be a link among victim, crime scene, and suspect.

In criminalistics, the scientific investigations are carried out through chemical, physical, and biological analyses that, according to the Italian judicial system, may be repeatable (art. 359 of the Code of Criminal Procedure) or not (art. 360 of the Code of Criminal Procedure) scientific and technical ascertainments, depending on several characteristics and circumstances. The judicial inspections and the scientific and technical ascertainments carried out by the forensic experts must be always done guarantying the rights of each involved part (accuse, defence, civil/offence parties) in the judicial proceeding. When it is possible, the experts have to apply non-destructive methods and to preserve a sample quote for further analyses. The analyses carried out on the evidence will establish the degree of similarity of evidence to associate or exclude a suspect to /from the victim and crime scene, comparing characteristics of the unknown samples (evidence of unknown provenance, named also questioned samples) with those of the known samples (evidence of known provenance, named also control samples). Characteristics of evidence that may be compared are individual or of class (Saferstein 2017) (Table 1). Individual characteristics allow to identify a person with an elevated degree of certitude (DNA or fingerprints), whereas the class characteristics allow to identify a group of persons/objects (Saferstein 2017).

TABLE 1. Some examples of individual and class characteristics of the physical evidence.

Individual characteristics	**Class characteristics**
Human DNA	Blood groups
Animal DNA	Geological and soil material
Plant DNA	Anthropogenic materials (glass, fibers, paper, plastics, hairs)
Fingerprints	Paints

The geological and soil materials are classified as class evidence (Table 1). Obtaining data with an elevated degree of certitude from these materials, through comparative analyses, is very arduous. Different values, ranging from very weak to very strong, may be attributed to the comparison depending on the match of biological, chemical, and physical evidence. But, as reported by one of the fathers of Forensic Geology, Raymond C. Murray, a factor that may assume a crucial role in such analyses is the finding of peculiar or rare particles (Murray 2004a). These may be used for strongly strengthen the degree of certitude of the comparative analyses.

The geological and soil evidence is studied by the Forensic Geology (also known as geoforensics or forensic geosciences). This criminalistic discipline applies the geosciences for solving criminal cases. A long history characterises this matter, based on scientific principles and methods adopted in most police laboratories around the world, especially in USA, United Kingdom, and Australia (Murray and Tedrow 1975; Palenik 1982; Lombardi 1999; Bull *et al.* 2004; Murray 2004a,b; Pye and Croft 2004; Bull *et al.* 2005; Pye 2005; Ruffell 2005; Ruffell and McKinley 2005; McKinley and Ruffell 2007; Morgan and Bull 2007; Pye 2007; Fitzpatrick, Raven, and Forrester 2009; Pirrie 2009; Ruffell and McKinley 2009; Ruffell 2010; Ruffell and McKinley 2014; Pirrie, Dawson, and Graham 2017; Werner *et al.* 2019; L. J. Donnelly *et al.* 2021; Fitzpatrick and L. Donnelly 2021). Several were the criminal cases solved by applications in the field of Earth Sciences. One among all, the case of the kidnapping and homicide of the honourable Aldo Moro (Lombardi 1999). Notwithstanding, unfortunately, in Italy today, there are not geologists involved in the law enforcements devoted to crime scene investigation, being required technical directors in the field of chemistry, biology, engineering, physics, and psychology. Few geologists working in the law enforcements today are retired or collaborated in the *riserva selezionata* forces of the *carabinieri* for a short period in the past years. This anomalous circumstance obliges the magistrates and judges to charge geologists, chosen among freelances or academics, to assist them with their scientific knowledge and expertise for solving crimes where geological and soil evidence are involved. With this in the mind, this paper aims at describing the main applications of Forensic Geology.

2. Forensic Geology

Forensic Geology (Murray and Tedrow 1975; Murray 2004b; Di Maggio *et al.* 2014; Somma and Costa 2022) is at least 150 years old, but its origin could be much older. This discipline started to become known in the criminological panorama with the histories written by the Scottish writer and physicist, Sir Arthur Ignatius Conan Doyle (1859-1930), the father of the characters of Sherlock Holmes and his assistant Dr. Watson. In most of his novels (A Study in Scarlet, The Sign of the Four, The Five Orange Pips, The Speckled Band, and The Problem of Thor Bridge), Conan Doyle prophesied the use of geological evidence in the identification approach to find the source of them during criminal investigations. In reality, Doyle was delegated to analyse the geological trace found in the horse hooves in a case of rustling. The comparative analyses carried out by Doyle allowed to exonerate a man accused of being responsible (Ruffell and McKinley 2009). Contemporaneously to Doyle, another forensic expert, Johann (Hans) Baptist Gustav Gross (1847-1915), was interested in geoforensics. Gross was an Austrian judge and prosecutor, expert on topography, geography, and mineralogy. It is believed that part of the Doyle's novels was influenced by the previous work done by Gross. The principles of Forensic Geology were applied for the first time in the mid 1800 to solve a casework of substitution of the original high value material contained in a barrel with low value rocks and sands. The barrel transported by train along the Prussian railway, that originally contained silver coins, was found at destination, devoid of the money and infilled with rocks and sands (Ruffell and McKinley 2009). Christian Gottfried Herenberg (1795-1876), a German naturalist, geologist, and expert in microscopy, was commissioned to solve the case (Berlin, Germany). He was delegated to analyse the microscopic features of some sand samples collected in the surrounding of the train stops, in order to compare them with those of the barrel's sands. Comparative analyses allowed to localize the source of the questioned sands in one of the train stations. These scientific results lead investigators to narrow down the list of suspects and finally to identify the author of the crime in a station worker (Ruffell and McKinley 2009).

Main activities carried out by geologists concern: i) sedimentological, palaeontological, mineralogical, petrographic, and geochemical analyses in order to investigate composition, textures, and structures of the coherent and incoherent rocks (or minerals); ii) geophysical surveys for exploring the underground characteristics, included the aquifers and ground searching for specific targets, by identifying geophysical anomalies; iii) geochemical surveys for exploring the extension and depth of groundwaters; iv) remote sensing inspections for characterizing the aspect of the territory or surface searching for specific targets. These investigations, typically diffused in the domain of the Earth Sciences, may be used by forensic geologists for solving crimes (Somma 2022), such as homicides, corpse concealments in the underground, kidnappings, hit and run incidents, sexual assaults, counterterrorism, animal maltreating and wildlife crimes, robberies, thefts in apartments, vandalism, stone-throwings, frauds and financial crimes, and environmental damages (L. J. Donnelly *et al.* 2021; Somma 2022; Somma *et al.* 2023a). In particular, the main activities, carried out by forensic geologists, may be subdivided in:

(1) conflict minerals (Spoto 2023) and fakes (Marra, Di Silvestro, and Somma 2023);
(2) comparative analyses and provenance studies of geological evidence (Pirrie, Dawson, and Graham 2017);
(3) analyses of shallow clandestine homicide graves and related ground searches (France *et al.* 1997);
(4) surface search for counterterrorism and disappearance cases (L. J. Donnelly *et al.* 2021);

(5) hydrogeological, geochemical (Morgan and Bull 2006; Spoto, Somma, and Crea 2021), and geophysical prospections (Davenport *et al.* 1990; Ruffell and Parker 2021; Somma 2022) for environmental crimes.

2.1. Conflict minerals and fakes. Conflict minerals are considered those minerals illegally extracted by miners forced to work at gunpoint by armed militants/rebels of terroristic and criminal organizations (Barume *et al.* 2016). The illegal incomes of the mineral trading in the clandestine markets plump civil wars, contributing to exploitation and violence phenomena against the human rights (L. J. Donnelly *et al.* 2021). Tin (cassiterite), tungsten (wolframite), tantalum (coltan), and gold are known as the "three TGs". In the case these and gold are exploited in conflict areas, such as Congo, Sudan, Zambia, Tanzania, Burundi, and Rwanda, they can be considered conflict minerals. Since 2021, after the regulation 2017/821 of the EU Parliament, the European Union regulates the supply chain of TGs. The regulation is aimed to ensure that EU importers of 3TGs meet international responsible sourcing standards and that EU smelters and refiners source 3TGs, responsibly. These initiatives can help to break the connection between conflict minerals and the illegal exploitation of them in the high-risk conflict areas. Also diamonds, in the case they are exploited in conflict areas, such as Angola, Congo, Guinea, Guinea-Bissau, Ivory Coast, Liberia, Sierra Leone, and Zimbabwe, may be considered conflict minerals (blood diamonds). Diamonds have for long times been useful to society, being a gemstone of great value and a material with large applications in many industrial divisions (Spoto 2023). The illicit activities may involve the trading of false geological materials, such as gemstones and fossils (Ruffell, Majury, and Brooks 2012; Ruffell and Schneck 2017; L. J. Donnelly *et al.* 2021). In such cases, mineralogists are required to ascertain the authenticity and provenance of gemstones by means of non-destructive methods, such as spectroscopy (Raman, FTIR). Fossils authenticity is ascertained by expert palaeontologists by means of comparative observations with authentic specimens (Marra, Di Silvestro, and Somma 2023).

2.2. Geological comparative analyses and provenance studies of geological evidence. The main aim of the comparison is to associate (or exclude) specimens of the soil/sediment inorganic (minerals and nano- to microfossils) and organic (vegetal and animal) components of unknown provenance sampled on human remains, shoes, clothing, work instruments, or motor vehicle, with (or from) soils/sediments of known provenance collected from the crime scene, home and work site of the suspect, or other sites of investigative interest (Ruffell and McKinley 2009; Di Maggio *et al.* 2014). The comparative analyses of geological evidence are based on techniques investigating colour (spectrophotometer and Munsell charts, Sugita and Marumo 1996; Somma *et al.* 2023d, Figure 2), grain size determination (wet and air-dry sieving and laser diffraction granulometry), texture (Bull and Morgan 2006), fossil content (OM and SEM, Table 2), mineralogy (OM, XRD, SEM-EDS, Table 2), and chemical and chemical-physical composition (ICP-MS, ICP-OES, XRF, RAMAN, FTIR, INAA, Table 2) (Ruffell and McKinley 2009; Di Maggio *et al.* 2014; L. J. Donnelly *et al.* 2021). Main basic analyses for revealing the composition, textures, and structures are synthesized in Table 2. Other sophisticated analyses (magnetic susceptibility, gravimetry, among many others) may be also carried out.

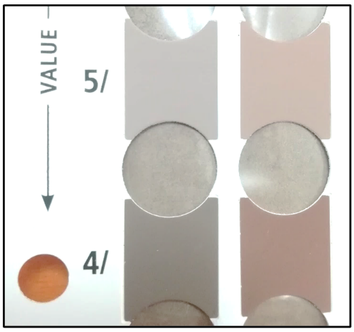

FIGURE 2. Determination of the colour of the finest fraction of a sandy volcanic soil (Stromboli volcano) by means of the Munsell colour charts (reddish gray - 2.5YR 5/1). Source: Author.

Comparisons of geological evidence may involve principles of stratigraphy as the principle of superposition that states that in a sedimentary succession the lowest bed will be older than the overlying one, that on its turn will be younger than the lower bed (Figure 3). This principle may be applied in criminal cases where a sequential layering of the geological evidence may be recognized. The layer at contact with the item (shoes, clothing, work instruments, vehicles, *etc.*) will be made up of the soil/sediment, the first one to be transferred from a site to the item. The successive layer will be composed of soil/sediment that will be transferred on the previous one.

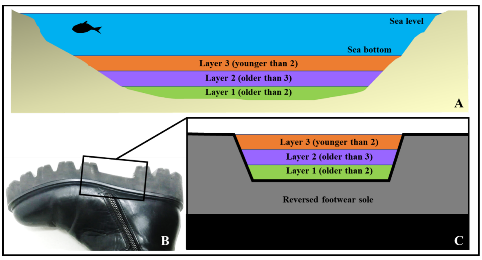

FIGURE 3. Stratigraphic principle of superposition applied to Forensic Geology. A. In a sedimentary basin, the sedimentation produces layers that make young from base to top. B. Footwear showing the sole with treads. C. The empty spaces of the sole may be filled by layers of soil/sediment whose order of transfer from the ground to the sole occurs from the oldest (layer 1 at contact with the sole) to the youngest (layer 3 the more external one). This sequence of layers may assist police to reconstruct the movements of the victims or the suspects. This principle is appliable also when the transfer occurs on clothing or other objects in movement. Source: Author.

Two, three, or several sequential strata of different soil/sediment may be commonly identified by an expert in the shoes and clothing of a suspect. A forensic expert with no skill on this topic could not recognize them and collect them without a microstratigraphic-based

TABLE 2. The main methods and techniques used by forensic geologists to analyse the soil/sediments/rocks and the related class characteristics (Ruffell and Wilson 1998; Pirrie *et al.* 2004; Ruffell and Wiltshire 2004; Bull and Morgan 2005, 2007; Bourguignon *et al.* 2019; Somma and Maniscalco 2023).

Matrices	**Methods and techniques**	**Analysed characteristics**	**Discipline**
Inorganic and anthropogenic components of geological samples (as it is), Thin-sections of resin-mounted sediments, rocks, and anthropogenic components of geological samples; smear slides of incoherent rocks	Optical Microscopy (OM) by stereo microscope, in transmitted and reflected light, with camera and workstation for image analysis	Texture (shape, roundness, luster, colour, coatings) structure, microfossils	Sedimentology, mineralogy, petrography, micropaleontology
Thin-sections of resin-mounted sediments, rocks, and anthropogenic components of geological samples; smear slides of incoherent rocks	Optical Microscopy (OM) by polarizing microscope, in transmitted and reflected light, with camera and workstation for image analysis	Mineral composition, texture, structure; microfossils	Sedimentology, mineralogy, petrography, micropaleontology
Grinded geological samples	Powder X-Ray Diffractometry (XRDP)	Mineral composition	Sedimentology, mineralogy, petrography
Inorganic and anthropogenic components of the forensic terrain (mounted on stubs or polished sections)	Scanning Electron Microscopy (SEM-EDS, QUEMSCAN)	Composition, texture, structure	Sedimentology, mineralogy, petrography
Fossils of the forensic terrain (mounted on stubs or polished sections)	Scanning Electron Microscopy (SEM), polarizing microscope	Micro- to nanofossils	Micropalaeontology
Inorganic and anthropogenic components of the forensic terrain	X-Ray Fluorescence (XRF)	Elemental qualitative determination	Geochemistry
Inorganic and anthropogenic components of the forensic terrain	μ-RAMAN and FTIR spectroscopy	Molecular qualitative determination	Mineralogy
Inorganic and anthropogenic components of the forensic terrain	Inductively Coupled Plasma-Mass Spectrometry (ICP-MS)	Elemental quantitative determination	Geochemistry
Inorganic and anthropogenic components of the forensic terrain	Inductively Coupled Plasma – Optical Emission Spectroscopy (ICP-OES)	Elemental quantitative determination	Geochemistry
Inorganic and anthropogenic components of the forensic terrain	Instrumental Neutron Activation Analysis (INAA)	Elemental quantitative determination	Geochemistry

sampling, destroying the layered structures. In the past, at beginning of 1900, George Popp solved different homicide cases by using micro-stratigraphy. Proper procedures of micro-stratigraphic sampling and analyses in the boot cleft may provide a small vertical-scale record of lateral movement through the crime scene (Ruffell and McKinley 2009).

2.2.1. *Case study 1. The homicide of Eva Disch, Frankfurt, Germany.* Geoforensics was applied for the first time in 1904 for solving a homicide case. A seamstress, named Eva Disch, was found lifeless, strangled with her scarf, in a bean field. The German forensic chemist, Georg Popp, was asked to examine a handkerchief found at the crime scene. It appeared stained with nasal *mucus* containing fragments of coal, tobacco, and particles of hornblende (questioned sample). Criminal investigations identified a suspect (K.L.), Popp retrieved from the subungual scraper of the suspect, traces of coal and hornblende (questioned sample) (Murray 2004a). Further inspections carried out on the suspect's trousers evidenced the occurrence of stains of stratified soil in which two layers were identifiable. The layer in contact with the cloth (questioned sample) was characterized by a mineral assemblage similar to that present at the crime scene (control sample). The overlying layer showed micas and other particles (questioned sample), comparable with those of the soil samples taken along the path between the crime scene and the suspect's house (control samples) (Murray 2004a). The results of the comparative analyses allowed to associate the suspect to the crime scene and, using the stratigraphic principle of superposition of strata, to reconstruct the suspect's movements from the crime scene, where he lost his dirty handkerchief and splashes of mica-rich mud transferred to the trousers, to his house where, during his return, a second layer of mud adhered to the trousers (Murray 2004a). Once confronted with the evidence gathered, K.L. admitted the crime and was convicted. In the days following his arrest, the local newspaper published an article entitled "The microscope as a detective" (Murray 2004a).

2.2.2. *Case study 2. The homicide of Margarethe Filbert, Bavaria, Germany.* At beginning of 1900 another homicide case was analysed by Georg Popp (Murray 2004a). A woman, Margarethe Filbert, was found lifeless, shot, in the woods near Rockenhausen. Popp was asked to study the hair found in the cadaver's hand and other material found during the investigation. Popp studied the hair and concluded that it belonged to the victim. Criminal investigations identified a suspect, A.S., found with traces of blood in the subungual scraper. The suspect's trousers and weapon were found in an abandoned castle located in the proximity of the crime scene. A.S. claimed they were left there prior to the murder. Popp observed the presence of encrusted and stratified soil (questioned sample) on the suspect's shoes. His wife declared that she cleaned the shoes the night before the murder. The first soil layer in contact directly on the leather of the shoes was rich in goose droppings; the second one appeared rich in lithoclasts of red sandstone; the third and more external layer was composed of a mixture of fragments of coal, bricks, and concrete (Murray 2004a). The first layer was characterized by soil with organic component similar to that present at the suspect's house (control sample). The second layer showed particles similar to those present in the crime scene soil (control sample). The third one presented particles, analogous to those of the soil exposed in the abandoned castle located in the proximity of the crime scene (control sample). The results of these comparative analyses allowed to associate the suspect to the crime scene and, using the principle of superposition, to reconstruct the suspect's displacements from his house to the crime scene and finally to the abandoned castle (Murray, 2004a). The careful collection of separated layers from the questioned items in both cases demonstrated the movements of the suspect (Murray 2004a).

2.2.3. *Case study 3. The corpse concealment of a militant of the republican–loyalist feuds, Belfast, Northern Ireland.* A shallow clandestine grave hosting the body of a victim of the feuds among the paramilitary groups was found in the countryside, near a quarry. Geological evidence was collected from the crime scene and the surrounding lanes. Samples appeared with evident visual differences allowing to divide them into three groups (brown silts and clays, white chalk soil, and dark brown organic-rich soil). An experiment carried out by Alastair Ruffell contemplated that a volunteer wearing a pair of boots walked on the crime scene, during a night with weather conditions analogous to those at the moment of the corpse concealment, in order to search for possible micro-stratigraphic evidence (Ruffell and McKinley 2009). Three different layers were found in the deep clefts of the boot tread. The first layer at contact with the sole consisted of a brown silt. The second layer was made up of a white chalk soil. The third and outer layer consisted of abundant dark brown organic-rich soil. These three different sequential layers replicated the sequence of movements of the suspect from the crime scene to the gateway of the quarry private property, recorded in the microstratigraphy collected in his footwears (Ruffell and McKinley 2009). This most recent experiment proved to be effective and allowed to validate the method applied by George Popp over 100 years before.

2.2.4. *Case study 4. The homicide of Aldo Moro, Rome, Italy.* Geoforensics was applied in Italy in 1978 for solving the homicide case of an Italian politician, the honorable Aldo Romeo Luigi Moro (Lombardi 1999; Murray 2004a). This application did acquire fame to Geoforensics in the Italian panorama of the Forensic Sciences. Moro was kidnapped by criminals (Red Brigades terrorists) and found lifeless, shot, in the trunk of a car (amaranth colour Renault 4) abandoned in the city centre of Rome, near the headquarters of the communist party. According to the reconstructions, Aldo Moro should have stayed within a den in the Via Montalcini hideout for fifty-five days, but doubts on the site of confinement continue to exist nowadays. A forensic geologist, Gianni Lombardi, and a botanist, Valerio Giacomini, were asked to analyse the geological and botanical evidence found in the trousers and moccasin soles (questioned samples) in order to ascertain the environment from where the materials were transferred to the victim. Geological and palaeontological evidence consisted of 1 g of sands. Textural analyses indicated that they consisted of beach sands. Botanical evidence found in the trouser's cuffs consisted of vegetal remains of *Centaurea aspera* (Lombardi 1999). The vegetational state of the plant indicated that this fragment detached from the original plant maximum 10-15 days before its finding in Moro's trousers. Bitumen traces, adhering to the sole of Moro's moccasins, were also found associated with these sands. The state of freshness of the bitumen traces indicated that this transfer occurred from a beach to the shoes in the days immediately preceding the finding of the corpse (Lombardi 1999). The investigations, carried out comparing the questioned samples with one hundred samples of sands (control samples) taken along 150 km of the *Lazio* coast, demonstrated that Moro walked on a beach in an area presumably stretched between Focene and Palidoro (Lombardi 1999), north of the Fiumicino airport (Figure 4), few days before his homicide. Investigators did not find any evidence of dens in that area.

Notwithstanding, recent investigations, carried out by the *Carabinieri RIS* on audio tapes found in a terrorist den, indicated that the original criminal project planned by the terrorists was not to leave the corpse in Rome. In the audio tapes, the following message was recorded: *Attention, message number 13 of the Red Brigades, Aldo Moro was judged by the people's court, this morning at 12 he was executed, you can find his body around the fort of San Martino. End of message*[1]. This might suggest that their original criminal intent could have been to abandon the corpse in Genoa. On the base of the above, it could be that Moro was brought by terrorists on that specific area of the *Lazio* beach, identified by Lombardi, a few days before his homicide, with the purpose of transferring him from Rome to Genoa (Somma 2022). This transfer could have been originally planned by boat from the *Lazio* coast or by car.

Finally, terrorists could have decided to renounce to the travel for the high risk to be caught or for an unexpected plan failure. The research carried out by Lombardi with

[1]Saita, F. (2015): Caso Moro, spunta audio inedito. Available online: http://www.adnkronos.com/fatti/cronaca/2015/09/30/caso-morospunta-audio-inedito-esclusiva-adnkronos_9VdeNE1pXlQJgtavJeEAKK.html (accessed online 10 September 2022).

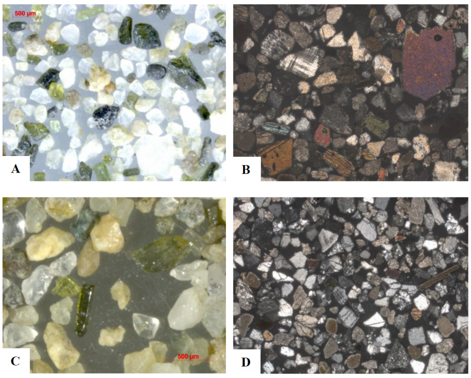

FIGURE 4. Beach sands from the *Lazio* coast. A: Focene beach sands observed under the stereomicroscope in reflected light. B: Focene beach sands in resin-mounted thin section observed under the petrographic microscope in crossed-polarized transmitted light. C: Passoscuro beach sands observed under the stereomicroscope in reflected light. D: Passoscuro beach sands in resin-mounted thin section observed under the petrographic microscope in crossed-polarized transmitted light. These sand grains are mainly composed of piroxenes, amphibole, olivine, biotite, muscovite, garnet, microcline, albite, quartz, orthoclase, calcite, oxides, and lithoclasts. Source: Author.

Giacomini demonstrated as for an effective study of geological evidence, geologists and botanists need to collaborate together in team (A. J. Brown 2006). In certain circumstances, especially when geological evidence is in trace or microtrace, the preparation of sub-samples for studying separately the inorganic and organic components is arduous and very time consuming. In such cases, the solution of working in team in the same laboratory on the same sample is useful (Morabito, Mondello, and Somma 2023; Morabito and Somma 2023; Somma 2023a; Somma *et al.* 2023c).

2.2.5. *Case study 5. The homicide of Enrique Camarena, Mexico.* One of the most famous cases involving Forensic Geology in America regarded the homicide case of Enrique Camarena Salazar (named Kiki) (McPhee 1997; Murray 2004a), an agent of the Drug Enforcement Administration (DEA) in the States who was working in Mexico. He disappeared in 1985 and was found lifeless on the ground, wrapped in a sheet, at a farm in Mexico (Michoacan state; Murray 2004a). An FBI expert carried out comparative analyses on soil traces (questioned sample) associated with the badly decomposed body remains and soil collected at the site where the body was discovered (control sample). Soil traces on the corpse were composed of grains of rhyolitic vesicular ashes containing cristobalite crystals in their cavities. The soil at the farm contained instead basaltic glass. Comparisons among the two samples suggested that they did not match. Further investigations in areas characterized by outcrops of rhyolitic ashes, based on informer data and the use of cadaver dogs, ascertained that the original gravesite was located in the Jalisco State Park of the Guadalajara Basin in Mexico (McPhee 1997; Murray 2004a). Camarena was murdered by drug traffickers of Mexican cartels, buried in a clandestine grave in the Jalisco zone, and finally exhumed and moved approximately 100 km to the south at the finding site at Michoacan, for a staging action of cover-up (Murray 2004a).

2.2.6. *Case study 6. Suspect murder case, Messina, Italy.* The author was involved by the judicial authority in the investigation regarding the reconstruction of the events occurred in a case of two missing persons in the countryside. A few days after the disappearance, the two missing persons were found lifeless by a canine unit of the firemen and a volunteer, on the ground in two different sites not too far from the last sighting of them. The geological and botanical evidence collected on the victims and on the sites was investigated following the methodological and scientific approach, described 40 years before by the geologist Lombardi and the botanist Giacomini in the report on the Moro's kidnapping and homicide case. Geological and botanical comparative analyses on different peculiar particles and particle associations allowed to link the victims to microenvironments with analogous features, ascertaining the *pre-mortem* presence of the victims on the site and reconstructing also the movements made by the two individuals in the finding area (Somma *et al.* 2023c).

2.3. Analyses of shallow clandestine homicide graves and the related ground search. Burials may be used by criminals to conceal underground moneys, loot, weapons, and corpses (France *et al.* 1997; Ruffell and Wiltshire 2004; Ruffell and McKinley 2005; Manhein, Listi, and Leitner 2006; Salsarola, Cattaneo, *et al.* 2009; Pringle and Jervis 2010; Harrison 2011; Larson, Vass, and Wise 2011; Pringle *et al.* 2012; Ruffell and Schneck 2017; Sagripanti *et al.* 2017; López Batista, Lòpez, and Batista 2018; Somma *et al.* 2018; Rocke, Ruffell, and L. J. Donnelly 2021; Rocke and Ruffell 2022; H. J. Byrd and Sutton 2023; Somma *et al.* 2023d; Tagliabue *et al.* 2023a,b). In shallow clandestine homicide graves, the geological and geographical evidence may provide valuable and useful criminological and criminalistic information on the offender behaviour and crime (Kamaluddin *et al.* 2021). The geological analyses of the soil/sediment diggability and observations on the grave's shape (walls, dimensions, and depths), carried out by geologists with the expert eye of forensic taphonomists (Marra 2023) and archaeologists, may reveal the possible digging modalities (by hand instruments or mechanical excavator) and other useful information. An under-dimensioned hole may depend on the fact that this was dug before the homicide, without a corpse for verifying during the excavation activities if the hole was enough capable to efficiently conceal the corpse. This could suggest if the concealment act was or not presumably premeditated. Notwithstanding, other reasons could be related to the lack of enough time or of skill/force for the realization of an excavation.

The geographical, geological, and botanical characteristics of a gravesite may play an important role in the site selection by concealer, being elements strongly influencing the human behavior. The selection of the burial site may be strictly dependent on his/her mental map. The Geographical Profiling (Hirschfield and Bowers 2001; Canter 2005; Douglas *et al.* 2013; Somma 2023b; Somma and Costa 2023), considering various factors that influence the mental map of the serial offenders in the choice of the crime scene, has several aspects in common with the factors adopted for the search for concealed bodies underground by forensic geologists (Somma and Costa 2022; Berezowski *et al.* 2023; Somma 2023b; Somma and Costa 2023). The geological methods used for searching activities may involve geology, geopedology, taphonomy (Marra 2023), remote sensing, applied geophysics, and geochemistry (L. J. Donnelly and Harrison 2013). In the case of the search and finding of a homicide grave, and the consequent recovery activities, the involvement of a multi-disciplinary teamwork of coroners, forensic anthropologists, archeologists, botanists, entomologists, and geologists is strongly recommended (Ruffell and McKinley 2009; Somma 2022; H. J. Byrd and Sutton 2023; Somma, Sutton, and J. H. Byrd 2023). The activities of recovery of a corpse from a homicide grave must be realized very careful and possible by experts, remembering that the grave is a crime scene and all the physical evidence must to be preserved. The excavation, before of the corpse's recovery realized by the coroner, should be done by a forensic archaeologist or stratigrapher. This expert may evaluate and suggest the best modality for the recovery of the body and apply the principles of the stratigraphic excavations where each bed covering the body is identified, photographed, and finally recovered to be carefully analysed for the search of physical evidence (biological traces and remains of clothing or objects belonging to the concealers, bullets, firearms, knifes, footprints). Such type of excavation allows to preserve intact the original shape of the hole providing useful information. Experimental gravesites realized by the author demonstrated as footprints on the ground of the excavation may be also preserved. In recent times, modern technologies, such as the laser scanning, may be applied for recording the original shape of the hole (Somma *et al.* 2023b) or for evidencing the typical depression forming on the homicide graves (Baldino *et al.* 2023). Finally, it must be underlined that the stratigraphic approach in the recovery activities should avoid the use of mechanical excavators, very inappropriate instrumentation that may seriously damage the human remains, contaminate the crime scene, and destroy the stratigraphy of the infill of the grave and of the outstanding soil/sediment.

2.3.1. *Case study 1. The clandestine grave on volcanic sands of Mount Etna (Catania, Italy).* A recent homicide grave was found on Mount Etna in Catania (Southern Italy) in June 2022. The finding of the burial was possible the day after the homicide, thanks to the confession of the self-confessed killer and concealer[2]. The burial site was very small and

[2]Palazzo, S. Ilsussidiario.net. "Elena Del Pozzo Non è Morta Subito"/ L'autopsia: "Più di 11 Coltellate, Una Letale…". 2022. Available online: https://www.ilsussidiario.net/news/elena-del-pozzo-non-e-morta-subito-lautopsia-piu-di-11-coltellate-una-letale/2361175/ (accessed online 18 June 2022). Iltempo.it. Elena Del Pozzo Uccisa Dalla Madre, i Carabinieri Raccontano la Confessione: "Come se Non si Fosse Resa Conto Del Gesto". 2022. Available online: https://www.iltempo.it/attualita/2022/06/14/video/elena-del-pozzo-uccisa-dalla-madre-movente-conferenza-carabinieri-video-32013337/ (accessed online 14 June 2022). Youtube.com. Elena Del Pozzo Uccisa a Catania, i Carabinieri: «Si Indaga Sul Luogo Del Delitto». Available online: https://www.youtube.com/watch?v=dI_zQPfM3AE (accessed online 15 June 2022). Youtube.com. Catania, Elena Del Pozzo è Morta Per Mano Della Madre. 2022. Available online: https://www.youtube.com/watch?v=SHPFl3EGvVw (accessed online 17 June 2022). Iltempo.it. Elena Del Pozzo Uccisa e Sepolta in un Campo: Il Ritrovamento Del Cadavere. Available online: https://www.iltempo.it/attualita/2022/06/14/video/elena-del-pozzo-ritrovato-cadavere-bimba-mascalucia-campo-video-32013850/ (accessed online 14 June 2022). Fanpage.it. Confessa la Mamma di Elena Del Pozzo, L'ha Uccisa Dopo L'asilo: "Gelosia Possibile Movente". 2022. Available online: https://www.youtube.com/watch?v=WMLM9lTGvqs (accessed online 14 June 2022). Fanpage.it. Omicidio Elena Del Pozzo: "La madre si è Procurata Una Zappa e Una Pala Per Occultare il Cadavere". 2022. Available online: https://www.youtube.com/watch?v=d6gY-IsKLhw (accessed online 15 June 2022). Youtube.com. Mascalucia, il Luogo Del Ritrovamento Visto Dall'alto. 2022. Available online: https://www.youtube.com/watch?v=HmWfSZo5Sbo (accessed online 14 June 2022). Siciliaunonews.com. Mascalucia, Bimba Morta. La madre: "L'ho Uccisa Girata, Non Volevo Guardarla". 2022. Available online: http://www.siciliaunonews.com/2022/06/mascalucia-bimba-uccisa-dalla-madre.html (accessed online 21 June 2022). Direttasicilia.it. Elena Uccisa a Coltellate e Sepolta, la Madre Aveva Comprato Pala e Zappa. 2022. Available online: https://www.direttasicilia.it/2022/06/

shallow, and dug by means of spade and shovel in volcanic sands. The diggability of the layer dug by means of hand instrumentation was evaluated easy. The area, analyzed through remote sensing and GIS (Somma and Costa 2022), allowed to define GIS-based RAG maps and search priority scenarios, ascertaining that the grave fell in a high priority red coded area, *i.e.* a site suitable for hosting a gravesite. This result validated a method previously based only on simulated crime scenes (Somma *et al.* 2018) and indicated as the percentage of the red coded area in the search area was very restricted and equal to 5%. This value was comprised among 2% and 6%, percentages obtained for day light concealments in simulated cases (Somma *et al.* 2018).

2.3.2. *Case study 2. The clandestine grave on alluvial deposits (Novellara, Italy).* A recent homicide clandestine grave was discovered at Novellara (Reggio Emilia, Northern Italy) on 18 November 2022[3]. The burial site was located in the shallow underground, in an area with the ruins of an abandoned cheese factory, at only 500 m of distance, beeline, from the disappearance site (house of the victim). This part of the factory, as observed through the multi-time reconstruction of satellite imagery, ruined ten years before during the earthquake of May 31th, 2012. Information provided by press organizations and national newscasts allowed the author to individuate the grave under an unsafe canopy (Figure 5), mostly collapsed on the ground, originating, a few meters to NE of the grave, a rubble *cumulus* made up of bricks with stacked wood beams partially covered by ivy creepers.The ground in the area of the burial appeared devoid of a concrete floor and covered by a few of bricks, wood beams, and sticks. The grave was oriented NE-SW and the corpse was disposed with the head to SW and the feet to NE. The gravesite was localized near the termination of this rubble *cumulus* and in front of the south-western edge of the opening of a ruined door. The skeletonized remains were found dressed, at around 1.6 m of deepness[4] from the topographic surface, covered by a layer made up of remained Holocene alluvial silty fine sands, light yellowish brown in color (mustard yellow). The corpse concealment, after the sediment infilling, was furtherly and partially covered with materials taken from the near rubble *cumulus*[5].

This superficial cover was presumably used as camouflage. The grave according to the investigators was presumably dug by means of shovels[6]. The diggability of the layer dug by means of hand instrumentation was evaluated easy. The finding of the shallow grave was

---

15/elena-uccisa-a-coltellate-e-sepolta-la-madre-aveva-comprato-pala-e-zappa/ (accessed online 15 June 2022). Agi.it; Greco, F.; Bruno, N. La Notte Sotto L'Etna di Elena, Uccisa Dalla Madre. 2022. Available online: https://www.agi.it/cronaca/news/2022-06-14/trovata-morta-bambina-rapita-catanese-17089667/ (accessed online 14 June 2022). Agi.it. Una Bimba di 5 Anni è Stata Sequestrata Nel Catanese da Persone Armate. 2022. Available online: https://www.agi.it/cronaca/news/2022-06-13/bambina-sequestata-catanese-17084057/ (accessed online 14 June 2022).

[3]Ponzi Luca (2022). Ritrovato il corpo di Saman Abbas. Il cadavere era nei pressi di un casolare in rovina, a poche centinaia di metri dalla casa della famiglia a Novellara (RE). Ora gli uomini del RIS analizzeranno i resti. https://www.rainews.it/tgr/emiliaromagna/articoli/2022/11/ritrovato-il-corpo-di-saman-abbas-38f22a51-8676-4376-9616-2fb21f72517b.html (accessed online 12 March 2023).

[4]https://mediasetinfinity.mediaset.it/video/quartogrado/il-giallo-di-saman-le-immagini-del-casolare-dove-sepolta-saman_F312094901011C13 (accessed online 12 March 2023).

[5]https://mediasetinfinity.mediaset.it/video/quartogrado/il-giallo-di-saman-aggiornamenti-sulle-ricerche-del-corpo_F312094901011C09 (accessed online 12 March 2023).

[6]https://tg24.sky.it/cronaca/approfondimenti/saman-abbas-storia (accessed online 12 March 2023)

FIGURE 5. Satellite imagery of the burial site from Google Earth.

possible thanks to the confession of one of the self-confessed concealers, notwithstanding one year and a half of intense searches involving cadaver dogs, ground penetrating radar (GPR), electro-magnetic instrumentations, and drone surveys[7]. The same site was inspected by dog units, but unfortunately no detection was revealed. A technique used to avoid this negative false consists into drilling the underground with a metal T-bar to favour the circulation of the air impregnated of cadaver scent up to the surface. It was unbelievable that this same site was also inspected 6 months before, in May, by a journalist who, whereas he was walking over the grave, unaware of the truth, suggested to investigate the suspect site for the search for the burial[8]. In particular, a video documentation on the Novellara burial, recently reported by a popular national TV program devoted to the black news[9] revealed to be significative for observing the modalities of excavations of the grave and recovery of the corpse. The vision of this video gave the opportunity for observing some moments of the activities carried out in the initial stage of the digging of the grave for the corpse's recovery. The critical observation of the video allowed to verify as the diggability degree and the consistency of the sediments were correctly tested by an operator of the *carabinieri* by means of a metal T-bar fixed in the deposits covering the body. The easiness of penetration of the bar suggested that the first layer, tens of centimetres thick, was very easy to dig, confirming the silty sands appearance of the sediments as reported in the official geological maps.

2.4. Surface search for counterterrorism and disappearance cases. Remote sensing surveys aimed at localizing sites of investigative interest, such as dens of terrorists or localities where persons disappeared lost in the countryside, may provide very useful investigative information (Davenport 2001; Ruffell 2002; Herrmann and Devlin 2008; Wolff and Asche 2009; Elmes, Roedl, and Conley 2014; Bunch, Kim, and Brunelli 2017; Somma 2022). The analyses of the territory (geologists, geographers, botanists) may be accomplished by forensic experts on photos, videos, and photograms, taken by cameramen and photographers, or of visible, UV (UltraViolet), infrared, ortho imaging, acquired through

[7] https://www.24emilia.com/bassa-reggiana-dopo-67-giorni-sospese-le-ricerche-di-saman-abbas/ (accessed online 12 March 2023).

[8] https://mediasetinfinity.mediaset.it/video/quartogrado/il-giallo-di-saman-le-immagini-del-casolare-dove-sepolta-saman_F312094901011C13 (accessed online 12 March 2023).

[9] https://mediasetinfinity.mediaset.it/video/quartogrado/la-tomba-nel-casolare-chi-ha-ucciso-saman_F312336501008C52 (accessed online 12 March 2023).

cameras mounted on airplane, helicopter, UAV (Unmanned Aerial Vehicle), and satellite. These data, uploaded into a GIS platform (ArcGIS, QGIS), may uncover secret localities, or detect the body of disappeared people in areas inaccessible for logistic, military, or risk reasons. The RAG map method, born in military environments during the second world war (Doyle and Bennett 1997; K. M. Brown and Keppel 2007; L. J. Donnelly and Harrison 2013; Ruffell and McAllister 2015), was recently applied also in Italy in the search planning for illegal burials. Remote sensing activities corroborated with the data obtained by the RAG maps allowed to strongly reduce the percentage of the high priority search areas both in several simulated cases and real cases (Somma *et al.* 2018; Somma and Costa 2022; Baldino *et al.* 2023; Somma *et al.* 2023c; Somma and Costa 2023; Somma *et al.* 2023d).

2.4.1. *Case study 1. Image intelligence, the case of Osama bin Laden, Afghanistan.* The most famous case of Image Intelligence and counterterrorism activities of the new *millennium* regarded Osama bin Laden, the al-Qaeda terrorist mastermind of the attacks to the World Trade Center in New York City and the Pentagon near Washington, occurred the September 11th, 2001. Bin Laden was taken up in a video shot in an outdoor location of Afghanistan in which an outcrop of rocks appeared at a few decimetres of distance in the background. The rocks appeared as marly limestones, well bedded and deformed by a system of dip-slip faults with an inclination of about 45°. Moreover, some peaks were accidently showed by the cameraman when he removed the camera from the tripod, at the end of the shot. The CIA asked a professor of the University of Nebraska, John Shroder, expert on the geography and geology of Afghanistan, to identify the areas shot by the video. The marly limestones were recognized as Mesozoic sedimentary deposits belonging to the Katawaz basin, whereas the rocky peaks were recognized as belonging to the Spīn Ghar mountains at SE of Kabul, in the eastern Afghanistan (Shroder 2008).

2.4.2. *Case study 2. Image intelligence, a case of disappearance (Italy).* The author was involved by the judicial authority in a case of missing person. The body was found in advanced state of putrefaction on the ground, in the countryside, a few days after his disappearance. The photograph of the corpse was recorded during the photographic survey made by means of Unmanned Aerial Vehicle (UAV), just the morning of the day after the last sight of the victim. Comparison of this image with the photographs taken by UAV the day of the finding allowed to ascertain that the corpse was arranged in the same position. This observation helped investigators to better define the date and time of the decease and to exclude other investigative hypotheses.

2.5. Environmental forensics. Environmental forensics is mainly devoted to the ascertainment of pollution in the natural inorganic matrices (Oivanki 1996; Ritz, Dawson, and Miller 2008; Ruffell and Dawson 2009; Ruffell and Kulessa 2009; Pirrie, Ruffell, and Dawson 2013; Ruffell 2013; Ruffell and Barry 2021; Spoto, Somma, and Crea 2021). Forensic geologists, according to the Italian rules of the professional organizations, may sample and analyse soil, superficial waters, and groundwaters. In each country, the legislative regulations establish their own law thresholds for each chemical element present in the different environmental matrices. During the criminal investigations, analytical and sampling protocols must be agreed and rigorously respected by the experts belonging to the accuse, defence, and civil parts. Polluted waters must be monitored in time in order to consider the concentration fluctuations. Concentrations may change during the year, especially in the underground waters, depending on weather conditions and recharge time of the aquifers. The source of contaminants, being natural or anthropogenic, must be carefully investigated and geological and hydrogeological conceptual models must be carefully planned for organizing useful sampling activities and geophysical surveys. In the study of groundwaters is imperative to search for waters from springs or wells located at higher altitude then the anthropogenic source suspected to be the source of the contaminant. In such cases, the chemical composition of these waters may be considered as control sample to be used to verify the natural or anthropogenic origin of the inspected contaminant. In cases of natural contamination, a study of the minerals responsible for the release of the specific chemical elements should be carefully carried out. In some circumstances, the water contamination may not be anthropogenic, but natural, depending on chemical elements released by the rock minerals, transferred into waters, as a consequence of complex chemical-physical interactions among waters and rocks (Spoto, Somma, and Crea 2021). In such cases, the pollution ascertained for presumed environmental crime could not depend on illegal human behaviours, but simply on natural causes. Forensic geologists involved in such investigations must be very cautious and careful to identify the pollution source. In suspect cases of natural contaminants, it is necessary to consider the kinematics governing the release of the investigated chemical element. The chemical-physical and geochemical approach on groundwaters has to be integrated with the physical characterization of the related aquifer for defining thickness, deepness, dimensions, and areal extension. This may be obtained by using geophysical prospections such as Electrical Resistivity Tomography (ERT) investigations calibrated with associated drillings (Table 3).

TABLE 3. The main matrices, disciplines, and investigations used by forensic geologists in environmental forensics (Spoto, Barone, and Somma 2023).

Matrices	**Disciplines**	**Investigations**
Soil and subsoil	Geology, Structural Geology, Stratigraphy, Sedimentology, Petrography, Applied Geophysics, Geochemistry	Geological and structural surveys, stratigraphic sections, geological conceptual models, sedimentological and petrographic analyses, chemical-physical analyses, ERT and seismic surveys, drilling
Superficial waters and groundwaters (springs, wells, rain water, and snow)	Hydrogeology, Geochemistry	Hydrogeological balance, Chemical-physical analyses, geological conceptual models

Geochemical and geophysical investigations associated with a full screening of the geological properties of the analysed territory may assist the judicial system to establish if the ascertained contamination depends on natural or anthropogenic causes, and in this case, it may be assigned to environmental pollution or environmental disaster according to the Italian legislation (law 68 of the 15 May 2015 introducing the crimes of environmental pollution and disaster in the Code of Criminal Procedure). Most of the Italian environmental crimes analysed by geologists concern the environmental crime of pollution (art. 452-*bis* of the Italian Code of Criminal Procedure) or the environmental crime of disaster (art. 452-*quater* of the Italian Code of Criminal Procedure).

The justice system defines culprit of environmental crime of pollution whoever illegally causes significant and measurable impairment or deterioration:

(1) of water or air, or extensive or significant portions of the soil or subsoil;
(2) of an ecosystem, biodiversity, including agriculture, flora or fauna.

This crime is punished with imprisonment from five to fifteen years.
The justice system alternatively defines the environmental crime of disaster as:

(1) the irreversible alteration of the balance of an ecosystem;
(2) the alteration of the balance of an ecosystem whose elimination is particularly onerous and achievable only with exceptional measures;
(3) the offense to public safety due to the relevance of the fact due to the extension of the compromise or its harmful effects or due to the number of people offended or exposed to danger.

This crime is punished with imprisonment from two to ten years, depending on the seriousness of the crime.
Most of these crimes are related to cases of groundwater and soil/subsoil contaminations produced by the infiltration in the underground of landfill leachate. In Italy, in the 70'-80', most of landfills were realized dumping wastes in the valleys, without to waterproof the bottom and the sides of the landfills. In such cases, the investigations may be very complex, as several territorial, ecosystemic, and public health aspects have to be considered, analysed, and monitored for long times. The experts to answer the questions posed by the judicial authority have to carefully consider all the requirements that the Code of Criminal Procedure considers for the evaluation of the specific type of environmental crime. These investigations, carried out by the judicial authority and their experts, may be very expensive consisting of drillings, geophysical surveys, and chemical analyses. Only in this way, the experts may provide accomplished answers that may assist the judicial authority to correctly reconstruct historical facts caused by pollution.

2.5.1. *Case study 1. Illegally burial of waste, County Tyrone, Northern Ireland.* The owner of a quarry was accused to have illegally buried toxic wastes in his property. The presence of the wastes in the subsoil was ascertained by means of excavation by mechanical excavator. Geologists analysed the geology and stratigraphy of the site as well as the hydrogeological features of the different units identified. A geological conceptual model, based on the acquired data, allowed to better plan, in terms of time and economical resources, investigations for evidence of polluted groundwaters (Ruffell 2013).

3. Discussion and conclusions

Forensic Geology may be used for solving several types of crimes. In light of the positive results of the cases here presented, it is evident that the judicial inspection at crime scene may benefit of an innovative multidisciplinary approach based on the application of principles and methods of the Earth and Natural Sciences. This approach is especially useful in criminal cases occurring outdoor in the countryside. Considering the great potentiality of Forensic Geology in the criminalistic panorama, it may be very important to provide academic formation (master courses, summer schools, events, seminars, field trainings), scientific research, and agreements with the judicial authority for promoting Forensic Geology among the main disciplines of Forensic Sciences used by police forces. These activities may slowly change the actual contradictory situation present in Italy. Some goals have already been achieved, but several challenges of the Forensic Geology in criminalistic field must be still faced.

References

Baldino, G., Ventura Spagnolo, E., Fodale, V., Pennisi, C., Mondello, C., Altadonna, A., Raffaele, M., Salmeri, F., Somma, R., Asmundo, A., and Sapienza, D. (2023). "The application of 3D virtual models in the judicial inspection of indoor and outdoor crime scenes". *Atti della Accademia Peloritana dei Pericolanti. Classe di Scienze Fisiche, Matematiche e Naturali* **101**(S1), A17. DOI: 10.1478/AAPP.101S1A17.

Barume, B., Naeher, U., Ruppen, D., and Schütte, P. (2016). "Conflict minerals (3TG): Mining production, applications and recycling". *Current Opinion in Green and Sustainable Chemistry* **1**, 8–12. DOI: 10.1016/j.cogsc.2016.07.004..

Berezowski, V., Mallett, X., Macgregor, D., Moffat, I., and Ellis, J. (2023). "More than an offender location tool: Geographic profiling and body deposition". *Journal of Police and Criminal Psychology*. DOI: 10.1007/s11896-021-09475-6.

Bourguignon, L., Dawson, L. A., Hellmann, A., Marlof, A., Fernadez Rodriquez, A., Repele, M., and Utehaag, S. (2019). "Best practice manual for the forensic comparison of soil traces." *ENFSI Website, ENFI-BPM-APS-02, Version 1, December 2019*.

Brown, A. J. (2006). "The use of forensic botany and geology in war crimes investigations in NE Bosnia". *Forensic science international* **163**(3), 204–210. DOI: 10.1016/j.forsciint.2006.05.025.

Brown, K. M. and Keppel, R. D. (2007). "Child abduction murder: An analysis of the effect of time and distance separation between murder incident sites on solvability". *Journal of forensic sciences* **52**(1), 137–145. DOI: 10.1111/j.1556-4029.2006.00328.x.

Bull, P. A. and Morgan, R. M. (2005). "Forensic Geoscience: Principles, Techniques and Applications". *Science and Justice* **45**(3), 169–170. DOI: 10.1016/S1355-0306(05)71658-0.

Bull, P. A. and Morgan, R. M. (2007). "Sediment fingerprints: A forensic technique using quartz sand grains-A response". *Science and Justice* **47**(3), 141–144. DOI: 10.1016/j.scijus.2007.07.001.

Bull, P. A., Morgan, R. M., Dunkerley, S., and Wilson, H. (2004). "Multi-technique comparison of source and primary transfer soil samples: an experimental investigation by D Croft and K Pye. A comment." *Science & Justice: Journal of the Forensic Science Society* **44**(3), 173–6.

Bull, P. A., Morgan, R. M., Dunkerley, S., and Wilson, H. E. (2005). "SEM-EDS analysis and discrimination of forensic soil". *Forensic science international* **155**(2-3), 222–225. DOI: 10.1016/j.forsciint.2005.07.017.

Bunch, A., Kim, M., and Brunelli, R. (2017). "Under our nose: the use of GIS technology and case notes to focus search efforts". *Journal of forensic sciences* **62**(1), 92–98. DOI: 10.1111/1556-4029.13218.

Byrd, H. J. and Sutton, L. (2023). "The Use of Forensic Entomology within Clandestine Gravesite Investigations". *Atti della Accademia Peloritana dei Pericolanti. Classe di Scienze Fisiche, Matematiche e Naturali* **101**(S1), A7. DOI: 10.1478/AAPP.101S1A7.

Canter, D. (2005). *Mapping murder: Walking in killers' footsteps*. Virgin Books Publishers.

Davenport, G. (2001). "Remote sensing applications in forensic investigations". *Historical Archaeology* **35**(1), 87–100. DOI: 10.1007/BF03374530.

Davenport, G., Griffin, T., Lindemann, J., and Heimmer, D. (1990). "Geoscientists and Law-Enforcement Professionals Work Together in Colorado". *Geotimes* **35**(7), 13–15.

Di Maggio, R., Barone, P., Pettinelli, E., Mattei, E., Lauro, S., and Banchelli, A. (2014). *Geologia Forense: Introduzione alle geoscienze applicate alle indagini giudiziarie*. Dario Flaccovio Editore.

Donnelly, L. J. and Harrison, M. (2013). "Geomorphological and geoforensic interpretation of maps, aerial imagery, conditions of diggability and the colour-coded RAG prioritization system in searches for criminal burials". *Geological Society, London, Special Publications* **384**(1), 173–194. DOI: 10.1144/SP384.10.

Donnelly, L. J., Pirrie, D., Harrison, M., Ruffell, A., and Dawson, L. A. (2021). "A guide to forensic geology". In: Geological Society of London. DOI: 10.1144/GFG.

Douglas, J., Burgess, A., Burgess, A., and Ressler, R. (2013). *Crime classification manual: A standard system for investigating and classifying violent crime*. John Wiley & Sons.

Doyle, P. and Bennett, M. (1997). "Military geography: terrain evaluation and the British Western Front 1914-1918". *Geographical Journal*, 1–24.

Elmes, G., Roedl, G., and Conley, J. (2014). *Forensic GIS: The role of geospatial technologies for investigating crime and providing evidence*. Vol. 11. Springer. DOI: 10.1007/978-94-017-8757-4.

Fitzpatrick, R. and Donnelly, L. (2021). *An introduction to forensic soil science and forensic geology: a synthesis*. DOI: 10.1144/SP492-2021-8.

Fitzpatrick, R., Raven, M., and Forrester, S. (2009). "A systematic approach to soil forensics: criminal case studies involving transference from crime scene to forensic evidence". *Criminal and environmental soil forensics* **105**. DOI: 10.1007/978-1-4020-9204-6_8.

France, D., Griffin, T., Swanburg, J., Lindemann, J., Davenport, G., Trammell, V., Travis, C., Kondratieff, B., Nelson, A., Castellano, K., *et al.* (1997). "NecroSearch revisited: further multidisciplinary approaches to the detection of clandestine graves". In: *Forensic taphonomy: the postmortem fate of human remains*. CRC Press, pp. 497–509. DOI: 10.1201/9781439821923.CH32.

Harrison, M. (2011). *Grave concerns, locating and unearthing human bodies*. DOI: 10.1080/00450618.2011.610823.

Herrmann, N. and Devlin, J. (2008). "Assessment of commingled human remains using a GIS-based approach". *Recovery, analysis, and identification of commingled human remains*, 257–269. DOI: 10.1007/978-1-59745-316-5_13.

Hirschfield, A. and Bowers, K. (2001). *Mapping and analysing crime data: Lessons from research and practice*. CRC Press. DOI: 10.1201/9781482268256.

Kamaluddin, M., Mahat, N., Mat Saat, G., Othman, A., Anthony, I., Kumar, S., Wahab, S., Meyappan, S., Rathakrishnan, B., and Ibrahim, F. (2021). "The psychology of murder concealment acts". *International journal of environmental research and public health* **18**(6), 3113. DOI: 10.3390/ijerph18063113.

Larson, D., Vass, A., and Wise, M. (2011). "Advanced scientific methods and procedures in the forensic investigation of clandestine graves". *Journal of Contemporary Criminal Justice* **27**(2), 149–182. DOI: 10.1177/1043986211405885.

Lombardi, G. (1999). "The contribution of forensic geology and other trace evidence analysis to the investigation of the killing of Italian Prime Minister Aldo Moro." *Journal of forensic sciences* **44**(3), 634–642. DOI: 10.1520/JFS14523J.

López Batista, M., Lòpez, S., and Batista, A. (2018). "The use of GIS in forensic archaeology to search clandestine graves in Uruguay". *Forensic Archaeology, Anthropology and Ecology* **2**(1), 61–74. DOI: 10.1103/PhysRevLett.106.235701.

Manhein, M., Listi, G., and Leitner, M. (2006). "The application of geographic information systems and spatial analysis to assess dumped and subsequently scattered human remains". *Journal of forensic sciences* **51**(3), 469–474. DOI: 10.1111/j.1556-4029.2006.00108.x.

Marra, A. (2023). "Taphonomical investigation applied to clandestine graves". *Atti della Accademia Peloritana dei Pericolanti. Classe di Scienze Fisiche, Matematiche e Naturali* **101**(S1), A6. DOI: 10.1478/AAPP.101S1A6.

Marra, A., Di Silvestro, G., and Somma, R. (2023). "Palaeontology applied to criminal investigation". *Atti della Accademia Peloritana dei Pericolanti. Classe di Scienze Fisiche, Matematiche e Naturali* **101**(S1), A4. DOI: 10.1478/AAPP.101S1A4.

McKinley, J. and Ruffell, A. (2007). “Contemporaneous spatial sampling at scenes of crime: advantages and disadvantages”. *Forensic Science International* **172**(2-3), 196–202. DOI: 10.1016/j.forsciint.2006.09.006.

McPhee, J. (1997). *Irons in the Fire*. Macmillan.

Morabito, M., Mondello, F., and Somma, R. (2023). “Macrobotanic data implementing Forensic Geology investigations”. *Atti della Accademia Peloritana dei Pericolanti. Classe di Scienze Fisiche, Matematiche e Naturali* **101**(S1), A13. DOI: 10.1478/AAPP.101S1A13.

Morabito, M. and Somma, R. (2023). “The crucial role of Forensic Botany in the solution of judicial cases”. *Atti della Accademia Peloritana dei Pericolanti. Classe di Scienze Fisiche, Matematiche e Naturali* **101**(S1), A11. DOI: 10.1478/AAPP.101S1A11.

Morgan, R. M. and Bull, P. A. (2006). “Data interpretation in forensic sediment and soil geochemistry”. *Environmental Forensics* **7**(4), 325–334. DOI: 10.1080/15275920600996248.

Morgan, R. M. and Bull, P. A. (2007). “The philosophy, nature and practice of forensic sediment analysis”. *Progress in Physical Geography* **31**(1), 43–58. DOI: 10.1177/0309133307073881.

Murray, R. (2004a). *Evidence from the earth: forensic geology and criminal investigation*. Mountain Press Publishing.

Murray, R. (2004b). “Forensic geology: yesterday, today and tomorrow”. *Geological Society, London, Special Publications* **232**(1), 7–9. DOI: 10.1144/GSL.SP.2004.232.01.02.

Murray, R. and Tedrow, J. (1975). *Forensic geology: Earth sciences and criminal investigation*. Rutgers University Press New Brunswick, NJ.

Oivanki, S. (1996). “Forensic geology: Geology investigation as a tool for enforcement of environmental regulations”. *Mississippi Geology* **17**(3).

Palenik, S. (1982). “Microscopic trace evidence-the overlooked clue. 1. Schneider, Albert looks at some string”. *Microscope* **30**(2), 93–100.

Picozzi, M. and Intini, A. (2009). *Scienze forensi: teoria e prassi dell’investigazione scientifica*. UTET giuridica.

Pirrie, D. (2009). “Forensic geology in serious crime investigation”. *Geology Today* **25**(5), 188–192. DOI: 10.1111/j.1365-2451.2009.00729.x.

Pirrie, D., Butcher, A., Power, M., Gottlieb, P., and Miller, G. (2004). “Rapid quantitative mineral and phase analysis using automated scanning electron microscopy (QemSCAN); potential applications in forensic geoscience”. *Geological Society, London, Special Publications* **232**(1), 123–136. DOI: 10.1144/GSL.SP.2004.232.01.12.

Pirrie, D., Dawson, L. A., and Graham, G. (2017). “Predictive geolocation: Forensic soil analysis for provenance determination”. *Episodes Journal of International Geoscience* **40**(2), 141–147. DOI: 10.18814/epiiugs/2017/v40i2/017016.

Pirrie, D., Ruffell, A., and Dawson, L. A. (2013). “Environmental and criminal geoforensics: an introduction”. *Geological Society, London, Special Publications* **384**(1), 1–7. DOI: 10.1144/SP384.20.

Pringle, J. and Jervis, J. (2010). “Electrical resistivity survey to search for a recent clandestine burial of a homicide victim, UK”. *Forensic science international* **202**(1-3), e1–e7. DOI: 10.1016/j.forsciint.2010.04.023.

Pringle, J., Ruffell, A., Jervis, J., Donnelly, L. J., McKinley, J., Hansen, J., Morgan, R. M., Pirrie, D., and Harrison, M. (2012). “The use of geoscience methods for terrestrial forensic searches”. *Earth-Science Reviews* **114**(1-2), 108–123. DOI: 10.1016/j.earscirev.2012.05.006.

Pye, K. (2005). “Forensic geology”. In: *Encyclopedia of Geology*. Ed. by R. Selley, L. Cocks, and I. Plimer. Vol. 2. Topics in Current Physics. Oxford, UK: Elsevier Academic, pp. 261–273.

Pye, K. (2007). *Geological and soil evidence: forensic applications*. CRC press.

Pye, K. and Croft, D. (2004). “Forensic geoscience: principles, techniques and applications”. In: Geological Society of London. DOI: 10.1144/GSL.SP.2004.232.

Ritz, K., Dawson, L. A., and Miller, D. (2008). *Criminal and environmental soil forensics*. Springer Science & Business Media. DOI: 10.1007/978-1-4020-9204-6.

Rocke, B. and Ruffell, A. (2022). "Detection of Single Burials Using Multispectral Drone Data: Three Case Studies". *Forensic Sciences* **2**(1), 72–87. DOI: 10.3390/forensicsci2010006.

Rocke, B., Ruffell, A., and Donnelly, L. J. (2021). "Drone aerial imagery for the simulation of a neonate burial based on the geoforensic search strategy (GSS)". *Journal of Forensic Sciences* **66**(4), 1506–1519. DOI: 10.1111/1556-4029.14690.

Ruffell, A. (2002). "Remote detection and identification of organic remains: An assessment of archaeological potential". *Archaeological Prospection* **9**(3), 115–122. DOI: 10.1002/arp.175.

Ruffell, A. (2005). "Searching for the IRA" disappeared": ground-penetrating radar investigation of a churchyard burial site, Northern Ireland." *Journal of Forensic Sciences* **50**(6), 1430–1435. DOI: 10.1520/JFS2004156.

Ruffell, A. (2010). "Forensic pedology, forensic geology, forensic geoscience, geoforensics and soil forensics". *Forensic Science International* **202**(1-3), 9–12. DOI: 10.1016/j.forsciint.2010.03.044.

Ruffell, A. (2013). "Solid and drift geology in forensic investigations". *Geological Society, London, Special Publications* **384**(1), 163–172. DOI: 10.1144/SP384.15.

Ruffell, A. and Barry, L. (2021). "The desktop study–an essential element of geoforensic search: homicide and environmental cases (west Belfast, Northern Ireland, UK)". *Geological Society, London, Special Publications* **492**(1), 39–53. DOI: 10.1144/SP492-2017-333.

Ruffell, A. and Dawson, L. A. (2009). "Forensic geology in environmental crime: Illegal waste movement & burial in Northern Ireland". *Environmental Forensics* **10**(3), 208–213. DOI: 10.1080/15275920903140346.

Ruffell, A. and Kulessa, B. (2009). "Application of geophysical techniques in identifying illegally buried toxic waste". *Environmental Forensics* **10**(3), 196–207. DOI: 10.1080/15275920903130230.

Ruffell, A., Majury, N., and Brooks, W. (2012). "Geological fakes and frauds". *Earth-Science Reviews* **111**(1-2), 224–231. DOI: 10.1016/j.earscirev.2011.12.001.

Ruffell, A. and McAllister, S. (2015). "A RAG system for the management forensic and archaeological searches of burial grounds". *Int. J. Archaeol* **3**, 1–8. DOI: 10.11648/j.ija.s.2015030101.11.

Ruffell, A. and McKinley, J. (2005). "Forensic geoscience: applications of geology, geomorphology and geophysics to criminal investigations". *Earth-Science Reviews* **69**(3-4), 235–247. DOI: 10.1016/j.earscirev.2004.08.002.

Ruffell, A. and McKinley, J. (2009). *Geoforensics*. John Wiley & Sons Ltd.

Ruffell, A. and McKinley, J. (2014). "Forensic geomorphology". *Geomorphology* **206**, 14–22. DOI: /10.1016/j.geomorph.2013.12.020.

Ruffell, A. and Parker, R. (2021). "Water penetrating radar". *Journal of Hydrology* **597**, 126300. DOI: 10.1016/j.jhydrol.2021.126300.

Ruffell, A. and Schneck, B. (2017). "International case studies in forensic geology: fakes and frauds, homicides and environmental crime". *Episodes Journal of International Geoscience* **40**(2), 172–175. DOI: 10.18814/epiiugs/2017/v40i2/017020.

Ruffell, A. and Wilson, J. (1998). "Shallow ground investigation using radiometrics and spectral gamma-ray data". *Archaeological Prospection* **5**, 203–215.

Ruffell, A. and Wiltshire, P. (2004). "Conjunctive use of quantitative and qualitative X-ray diffraction analysis of soils and rocks for forensic analysis". *Forensic science international* **145**(1), 13–23. DOI: 10.1016/j.forsciint.2004.03.017.

Saferstein, R. (2017). *Criminalistics: An introduction to forensic science*.

Sagripanti, G., Villalba, D., Aguilera, D., and Giaccardi, A. (2017). "Advances of forensic geology in Argentina: Search with non-invasive methods for victims of enforced disappearance". *Bolet in de Geologia* **39**(3), 55–69. DOI: 10.18273/revbol.v39n3-2017004.

Salsarola, D., Cattaneo, C., *et al.* (2009). "Archeologia forense". In: *Scienze Forensi: teoria e prassi dell'investigazione scientifica*. UTET.

Shroder, J. (2008). "Remote sensing and GIS as counterterrorism tools for homeland security: The case of Afghanistan". *Geospatial Technologies and Homeland Security: Research Frontiers and Future Challenges*, 11–33. DOI: 10.1007/978-1-4020-8507-9_2.

Somma, R. (2022). "Advances in Flipped Classrooms for Teaching and Learning Forensic Geology". *Education Sciences* **12**(6), 403. DOI: 10.3390/educsci12060403.

Somma, R. (2023a). "A multidisciplinary approach based on the cooperation of forensic geologists, botanists, and engineers: Computed Axial Tomography applied to a case work". *Atti della Accademia Peloritana dei Pericolanti. Classe di Scienze Fisiche, Matematiche e Naturali* **101**(S1), A12. DOI: 10.1478/AAPP.101S1A12.

Somma, R. (2023b). "The space and time dimensions in the criminal behaviour of lust murderers". *Atti della Accademia Peloritana dei Pericolanti. Classe di Scienze Fisiche, Matematiche e Naturali* **101**(S1), A19. DOI: 10.1478/AAPP.101S1A19.

Somma, R., Altadonna, A., Cucinotta, F., Raffaele, M., Salmeri, F., Baldino, G., Ventura Spagnolo, E., and Sapienza, D. (2023a). "The technologies of Laser Scanning and Structured Blue Light Scanning applied to criminal investigation: case studies". *Atti della Accademia Peloritana dei Pericolanti. Classe di Scienze Fisiche, Matematiche e Naturali* **101**(S1), A15. DOI: 10.1478/AAPP.101S1A15.

Somma, R., Baldino, G., Altadonna, A., Asmundo, A., Fodale, V., Gualniera, P. a. M., Pennisi, C., Raffaele, M., Salmeri, F., Ventura Spagnolo, E., and Sapienza, D. (2023b). "Education and training activities in forensic and biomedical sciences: The Laser scanner technology". *Atti della Accademia Peloritana dei Pericolanti. Classe di Scienze Fisiche, Matematiche e Naturali* **101**(S1), A16. DOI: 10.1478/AAPP.101S1A16.

Somma, R., Cascio, M., Cucinotta, F., Mondello, F., and Morabito, M. (2023c). "Recent advances in forensic geology and botany for the reconstruction of event dynamics in outdoor crime scenes: a case study". *Atti della Accademia Peloritana dei Pericolanti. Classe di Scienze Fisiche, Matematiche e Naturali* **101**(S1), A10. DOI: 10.1478/AAPP.101S1A10.

Somma, R., Cascio, M., Silvestro, M., and Torre, E. (2018). "A GIS-based quantitative approach for the search of clandestine graves, Italy". *Journal of forensic sciences* **63**(3), 882–898. DOI: 10.1111/1556-4029.13677.

Somma, R. and Costa, N. (2022). "Unraveling Crimes with Geology: As Geological and Geographical Evidence Related to Clandestine Graves May Assist the Judicial System". *Geosciences* **12**(9), 339. DOI: 10.3390/geosciences12090339.

Somma, R. and Costa, N. (2023). "GIS-based RAG-coded search priority scenarios for predictive maps to prevent future serial serious crimes: the case study of the Florence Monster". *Atti della Accademia Peloritana dei Pericolanti. Classe di Scienze Fisiche, Matematiche e Naturali* **101**(S1), A18. DOI: 10.1478/AAPP.101S1A18.

Somma, R. and Maniscalco, R. (2023). "Forensic geology applied to criminal investigation: a case report". *Atti della Accademia Peloritana dei Pericolanti. Classe di Scienze Fisiche, Matematiche e Naturali* **101**(S1), A9. DOI: 10.1478/AAPP.101S1A9.

Somma, R., Spoto, S. E., Raffaele, M., and Salmeri, F. (2023d). "Measuring color techniques for forensic comparative analyses of geological evidence". *Atti della Accademia Peloritana dei Pericolanti. Classe di Scienze Fisiche, Matematiche e Naturali* **101**(S1), A14. DOI: 10.1478/AAPP.101S1A14.

Somma, R., Sutton, L., and Byrd, J. H. (2023). "Forensic geology applied to the search for homicide graves". *Atti della Accademia Peloritana dei Pericolanti. Classe di Scienze Fisiche, Matematiche e Naturali* **101**(S1), A5. DOI: 10.1478/AAPP.101S1A5.

Spoto, S. E. (2023). "Illicit trafficking of diamonds: new frontiers". *Atti della Accademia Peloritana dei Pericolanti. Classe di Scienze Fisiche, Matematiche e Naturali* **101**(S1), A3. DOI: 10.1478/AAPP.101S1A3.

Spoto, S. E., Somma, R., and Crea, F. (2021). "Using a forensic-based learning approach to teach geochemistry". *Atti della Accademia Peloritana dei Pericolanti. Classe di Scienze Fisiche, Matematiche e Naturali* **99**(S1), A31. DOI: 10.1478/AAPP.99S1A31.

Spoto, S. E., Barone, S., and Somma, R. (2023). "An introduction to forensic geosciences". *Atti della Accademia Peloritana dei Pericolanti. Classe di Scienze Fisiche, Matematiche e Naturali* **101**(S1), A1. DOI: 10.1478/AAPP.101S1A1.

Sugita, R. and Marumo, Y. (1996). "Validity of color examination for forensic soil identification". *Forensic science international* **83**(3), 201–210. DOI: 10.1016/S0379-0738(96)02038-5.

Tagliabue, G., Masseroli, A., Ern, S., Comolli, R., Tambone, F., Cattaneo, C., and Trombino, L. (2023a). "The Fate of Phosphorus in Experimental Burials: Chemical and Ultramicroscopic Characterization and Environmental Control of Its Persistency". *Geosciences* **13**(2), 24. DOI: 10.3390/geosciences13020024.

Tagliabue, G., Masseroli, A., Mattia, M., Sala, C., Belgiovine, E., Capuzzo, D., Galimberti, P., Slavazzi, F., Cattaneo, C., and Trombino, L. (2023b). "Thanatogenic Anthrosols: a geoforensic approach to the exploration of the Sepolcreto of the Ca' Granda (Milan)". *Atti della Accademia Peloritana dei Pericolanti. Classe di Scienze Fisiche, Matematiche e Naturali* **101**(S1), A8. DOI: 10.1478/AAPP.101S1A8.

Werner, D., Burnier, C., Yu, Y., Marolf, A., Wang, Y., and Massonnet, G. (2019). "Identification of some factors influencing soil transfer on shoes". *Science & Justice* **59**(6), 643–653. DOI: 10.1016/j.scijus.2019.07.004.

Wolff, M. and Asche, H. (2009). "Towards geovisual analysis of crime scenes–a 3D crime mapping approach". In: *Advances in GIScience: Proceedings of the 12th AGILE Conference*. Springer, pp. 429–448. DOI: 10.1007/978-3-642-00318-9_22.

---

[a] Università degli Studi di Messina,
Dipartimento di Scienze Matematiche e Informatiche, Scienze Fisiche e Scienze della Terra,
Viale F. Stagno d'Alcontres 31, 98166 Messina, Italy

[b] Accademia Peloritana dei Pericolanti,
Palazzo Università,
Piazza Pugliatti 1, 98122 Messina, Italy

Email: rsomma@unime.it

Paper contributed to the workshop on "Advances and applications in geoforensics: Unraveling crimes with geology", held in Messina, Italy (26 September 2022) under the patronage of the *Accademia Peloritana dei Pericolanti*

Manuscript received 03 March 2023; published online 12 September 2023

© 2023 by the author(s); licensee *Accademia Peloritana dei Pericolanti* (Messina, Italy). This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution 4.0 International License (https://creativecommons.org/licenses/by/4.0/).