DOI: 10.1478/AAPP.101S1A10

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

Vol. 101, No. S1, A10 (2023)

RECENT ADVANCES IN FORENSIC GEOLOGY AND BOTANY FOR THE RECONSTRUCTION OF EVENT DYNAMICS IN OUTDOOR CRIME SCENES: A CASE STUDY

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ABSTRACT. The present research is devoted to criminal investigation regarding the disappearance of two persons suspected to be kidnapped. The multi-disciplinary investigation based on the application of Forensic Geology and Botany allowed to ascertain the *pre-mortem* active presence of the victims on the event scene. The results of the geological and botanical characterization accomplished on the traces collected on the victims and their belongings (unknown samples) and soils and plants sampled on the scene of events (known samples), allowed to ascertain with a high degree of compatibility as the source of the unknown samples could derive from environments with characteristics similar to those found in the scene of events, suggesting a same common origin for the analysed unknown and known specimens. Peculiar minerals (calcium phosphate rich clays and dolostones), very abundant vegetal particles (thorns and seeds of *Erica arborea*), and algae associations were particularly useful in linking the victims to the scene of events. The results of the comparative analyses provided fundamental info-investigative data useful for establishing the *pre-mortem* active presence of the victims on the scene. Furthermore, the most significant positive matches found allowed reconstructing a very detailed walking carried out by the two victims on the event site in the hours immediately preceding their death. These implications were of paramount importance for the judicial system in the solution of this criminal case. The careful examination of mineral composition, textural features as well as of the peculiar assemblages of inorganic and vegetal materials from unknown and known specimens carried out in the case work revealed to be able to provide very strong geological and botanical evidence for supporting criminal investigations. These robust results were achieved by the experts involved in long time-consuming and careful activities and examinations. Furthermore, the geological and botanical investigation carried out demonstrated as the analyses of the relationships ascertained between the victims and the surrounding environment could also support the coroner's decision on the manner of death and facilitating the understanding of the event dynamics.

1. Introduction

Crime scenes and scenes of events related to suspected deaths occurring outdoor, in rural area or farmland, are significantly different from scenes happened indoor. In outdoor scenes there is a high probability that a transfer of inorganic and organic materials occurs from the soil (sediment) present on the ground to the victim or perpetrator (Ruffell and McKinley 2008), linking the presence of the crime actors to the scene. The comparative analyses of the inorganic and organic traces and micro traces collected from the victim and suspect, included their belongings, with the sediments/soils and vegetation collected on the event sites may provide important info-investigative data useful for reconstructing several circumstances and the event dynamics in criminal cases (Somma 2022).

The present paper is aimed to describe the holistic methodological approach used by the uncharged forensic geologist (R.S.) in an investigation carried out a few years ago for a case of two missing persons, suspected to be kidnapped. Scientific investigations were requested by the judicial authority and carried out by a team of forensic experts (in legal medicine, veterinary, entomology, botany, and geology) for analysing the physical evidence in order to determine the differential diagnosis between natural and forensic interest deaths. In complex serious crimes occurred outdoor, such as this one, it is recommended the use of a trans- and multidisciplinary approach, crucial for better assisting judicial authority and law enforcements in criminal investigation. In such circumstance, a geological and botanical investigation was carried out. The expertise of both geologists and botanists were involved in this case work, in the wake of the investigation carried out by Lombardi and Giacomini for the kidnapping and homicide of Aldo Moro (Lombardi 1999).

2. Forensic Geology

Forensic Geology (also known as Forensic Geosciences or Geoforensics) is a criminalistic discipline of the Forensic Sciences that applies principles, techniques, and methods of the geosciences for solving criminal cases (Murray and Tedrow 1975; Palenik 1982; Tindall 1994; Lombardi 1999; Bull *et al.* 2004; Murray 2004a,b; Pye and Croft 2004; Bull and Morgan 2005; Bull, Morgan, and Dunkerley 2005; Pye 2005; Ruffell and McKinley 2005; McKinley and Ruffell 2007; Pye 2007; Ruffell and McKinley 2008; Fitzpatrick, Raven, and Forrester 2009; Pirrie 2009; Ruffell 2010; Ruffell and McKinley 2014; Pirrie, Dawson, and Graham 2017; Werner *et al.* 2019; Donnelly *et al.* 2021; Fitzpatrick and Donnelly 2021; Somma 2022, 2023a,b,c; Spoto, S. Barone, and Somma 2023). Forensic geologists may assist the police and the judicial authority or the lawyers in most serious crimes, such as suspect deaths (homicides or suicides) and corpse concealments (France *et al.* 1997; Ruffell and Wilson 1998; Ruffell 2004, 2005; Manhein, Listi, and Leitner 2006; Salsarola and Cattaneo 2009; Harrison 2011; Larson, Vass, and Wise 2011; Pringle *et al.* 2012; Donnelly and Harrison 2013; Ruffell *et al.* 2017; Sagripanti *et al.* 2017; López Batista, Rodríguez López, and Fieguth Batista 2018; Somma *et al.* 2018; Rocke, Ruffell, and Donnelly 2021; Rocke and Ruffell 2022; Byrd and Sutton 2023; Marra 2023; Somma, Sutton, and Byrd 2023; Tagliabue *et al.* 2023a,b). Other crimes treated by geologists may concern kidnappings, hit and run incidents, sexual assaults, counterterrorism, animal maltreating and wildlife crimes, robberies, thefts in apartments, vandalism, stone-throwings, fossil (Ruffell, Majury, and Brooks 2012; Ruffell and Schneck 2017; Marra, Di Silvestro, and Somma 2023) and gemstones frauds (Spoto 2023), financial crimes, and environmental damages. Principles, techniques, and methods of mineralogy, petrography, sedimentology, and micropalaeontology (Somma and Maniscalco 2023) may be used with a multidisciplinary approach in order to compare the related characters of geological traces and microtraces (unknown samples) with those of sediment and soils collected for control purposes (known samples). Geological traces and sediment and soils may be distinguished in unknown and known samples, if their origin or provenance is unknown and known, respectively. Terms, such as "control samples", should be avoid according to the "Best Practice Manual for the Forensic Comparison of Soil Traces" (Bourguignon *et al.* 2019).

On the other hand, disciplines such as geophysics (Davenport *et al.* 1990; Ruffell and Parker 2021), hydrogeology, environmental geology (Oivanki 1996; Ritz, Dawson, and Miller 2009; Ruffell and Dawson 2009; Ruffell and Kulessa 2009; Pirrie, Ruffell, and Dawson 2013; Ruffell *et al.* 2018; Ruffell and Barry 2021), remote sensing, GIS geodatabase, and imagery analyses (Doyle and Bennett 1997; Davenport 2001; Ruffell 2002; K. M. Brown and Keppel 2007; Herrmann and Devlin 2008; Ruffell and McKinley 2008; Wolff and Asche 2009; Pringle and Jervis 2010; Donnelly and Harrison 2013; Elmes, Roedl, and Conley 2014; Ruffell and McAllister 2015; Bunch, Kim, and Brunelli 2017; Somma *et al.* 2018), geography (Canter 2003; Hirschfield and Bowers 2003; Douglas *et al.* 2006; Kamaluddin *et al.* 2021; Pizzichi 2022; Somma and Costa 2022; Somma 2023b,c; Somma and Costa 2023), and geochemistry (Morgan and Bull 2006; Spoto, Somma, and Crea 2021) may be applied, using a multidisciplinary approach, in complex cases of environmental crimes (waste dumps responsible for natural matrices' pollution and environmental disaster, trafficking and abandonment of radioactive material, *etc.*) or in the search activities for concealed items in the underground (corpses, weapons, money, stolen goods). The geological matrices usually analysed by forensic geologists are waters, sediments, and soils. Sediments and soils may be composed of minerals and fossils. The soil system is more complex than classical sediments, because it, together inorganic particles, hosts organic (animal and vegetal matter) and anthropogenic components, due to pedogenesis and human-environmental interactions. The forensic analyses of geological and soil traces are mostly comparative and aimed to ascertain if an unknown sample (related to a trace) matches or does not match with a known sample (for example collected from crime scene, *alibi* site, or *museum* collection). In most cases, understanding if two compared geological samples may derive from the same source, identifying in the field a specific microenvironment, may be of paramount importance. In such circumstances, the task of the expert consists not only in simply ascertaining if two samples match or don't match, but also in evaluating the comparative data. According to the Forensic Sciences, geological and soil evidence are classified as "class evidence" and cannot allow the identification of a specific element, as in the case of "identity evidence" (DNA and fingerprints) (Saferstein 2017). As a matter of facts, the class evidence consists of materials whose provenance derives rather from a class of substances. Among the main class evidence there are minerals/rocks, paintings, fibres, and glasses. For this reason, forensic geologists for ascertaining a significative comparison among unknow and known geological samples have to work hardly in order to provide strong evidence in a law court. A geological evidence may be considered strong if the results of the comparative analyses are based on the evaluation of a considerable number of features regarding the compositions, structure, and texture of the geological evidence as well as of chemical (pH, Eh, cation exchange), physical (magnetic susceptibility), and biological characteristics (DNA of soil organisms). Moreover, whatever protocol or analysis is adopted by the expert, the goal of every forensic geologist should be to search for and recognize in geological evidence of unknown origin the possible presence of "peculiar, singular, rare, unusual" particles (Sugita and Marumo 1996; Murray 2004a; Di Maggio *et al.* 2013; and references therein). By the way, these may include for example small particles of anthropogenic (fragments of various types of paint, Di Maggio *et al.* 2013; plasterboard, Ruffell and Dawson 2009), inorganic (minerals such as gahnite, Murray 2004a) or vegetal (spores, pollen, seeds, *etc*., Sugita and Marumo 1996) origin. The identification of such particles also in the sample of known origin (soils/sediments/rocks), during comparative analyses, greatly strengthens the determination of compatibility among specimens and source and the value of the geological evidence. The main geological analyses (Table 1) carried out on the evidence are mineralogical, petrographic, geochemical (petrographic microscope, stereomicroscope, SEM-EDS, QuemSCAN, XRD, XRF, INAA, ICP-MS, *etc*.), sedimentological (laser granulometer and mechanical siever for grain size separation and determination, stereomicroscope for morphological and morphometric analyses), and colorimetric (spectrophotometer, Munsell charts, Murray 2004a; Somma *et al.* 2023c).

TABLE 1. Geological characterization for comparing inorganic component of geological and soil evidence and defining provenance.

Main methods	**Bibliography**
1 Stereomicroscopy and petrographic microscopy (mineralogy and texture)	1 (Murray 2004a; Morgan and Bull 2006; Bourguignon *et al.* 2019)
2 SEM-EDS / QuemSCAN (mineralogy)	2 (Pirrie *et al.* 2004; Ruffell and McKinley 2008; Bourguignon *et al.* 2019)
3 XRD (mineralogy)	3 (A. G. Brown 2006; Ruffell and Wiltshire 2004; Ruffell and McKinley 2008) (Bourguignon *et al.* 2019)
4 XRF / µXRF (mineralogy)	4 (Bourguignon *et al.* 2019)
5 Vibrational spectroscopy - Infrared and Raman spectroscopy	5 (Chalmers, Edwards, and Hargreaves 2012; Di Maggio *et al.* 2013)
6 Spectrometry - ICP-MS, ICP-OES (chemical composition)	6 (Bourguignon *et al.* 2019)
7 Texture of the quartz grain surface (texture)	7 (Bull and Morgan 2006; Bourguignon *et al.* 2019)
8 Particle size distribution (texture)	8 (Morgan and Bull 2007; Bourguignon *et al.* 2019)
9 Color	9 (Sugita and Marumo 1996; Bourguignon *et al.* 2019; Somma *et al.* 2023c)
10 pH	10 (Bourguignon *et al.* 2019)
11 Organic matter content (loss on ignition)	

3. Forensic Botany

Forensic Botany is a criminalistic discipline of the Forensic Sciences that applies principles, techniques, and methods of the botany for solving criminal cases (Ruffell and McKinley 2008; Picozzi and Intini 2009; Hall 2012; Saferstein 2017; Morabito, Mondello, and Somma 2023; Morabito and Somma 2023). Plant specimens, such as terrestrial plants, algae, and fungi, in fragments, individuals or populations, can be used as evidence for linking objects or people to the crime scene and scene of events (Coyle *et al.* 2005; Hard and Wallace 2012). Some typical vegetal elements analysed in forensics may be represented by seeds, thorns, leaf or shrub fragments, pollen, microalgae (e.g. diatoms; Table 2) found as traces and microtraces in clothing, footwear, or corpses related to the actors of a crime (Ladd and Lee 2005). The transfer to victim and suspect of vegetal remains from the scene, where they are present as the vegetal organic component of the soil or as plants growing on site, can be used to link them to the scene or to disprove any relation. Botanical evidence may be found in most of the event scenes, but certainly these are more present in outdoor scenes in the countryside (Ladd and Lee 2005). When the scene of events is known, the most important reference collection is made up of plants, or fragments, found at the scene itself and, in particular, any piece of evidence associated with a relevant body or object. Such evidence has to be identified usually by comparing unknown and known samples (Ladd and Lee 2005). The study of the plant taxonomy can provide useful investigative information for events occurring outdoor where vegetation is prevalent. The different aspects of Forensic Botany involve anatomy, systematics, palynology, and plant ecology (Horswell *et al.* 2002; Coyle *et al.* 2005; Hall 2012 among many others). Most of the analyses on organic evidence provide potential class evidence, but in some circumstances, the possibility to identify the DNA of *bacteria* (Table 2) and other organisms (such as pollens and plants in general) allows to consider the specimens as individual evidence (*sensu* Saferstein 2017). The DNA determination in comparative analyses may give to botanical evidence a very strong value. Notwithstanding, considering the sensitive of DNA traces and their easy perishability in the outdoor environments, it is not always possible to extract valuable DNA traces from botanical samples.

TABLE 2. Biological characterization for comparing samples and studying provenance.

Main methods	**Bibliography**
Pollen	(Bruce and Dettmann 1996)
DNA *bacteria*	(Stone *et al.* 2023)
	(Horswell *et al.* 2002)
Plants (seeds, fruits, leaves, *etc.*)	(Coyle *et al.* 2005)

4. Case study

The judicial authority and law enforcements directed investigations for a kidnapping case regarding two missing individuals, disappeared from their home for several days. The two subjects (victims 1 and 2) were found lifeless in two separate sites, in the countryside not too far from the last sighting site.

5. Materials and methods

5.1. Planning of activities. On the base of the questions posed to the expert and the preliminary data acquired, a methodological approach was planned. Seven different work phases were carried out during a period of one year. These phases in some circumstances were accomplished also contemporaneously. The organization of the various stages of work was synthesized in Table 3.

Geological and botanical investigations were carried out in order to ascertain the possible *pre-mortem* presence of the two missing persons on the sites of finding. Analyses were also aimed to reconstruct the possible walking made by them in the last hour of life and to search for a clandestine grave that could have hypothetically host the body of one of the victims, during an initial stage before the finding on the ground of the skeletonized human remains.

5.2. Materials and sampling activities. Sampling of the geological and botanical traces and micro traces (unknown samples) was carried out on the footwears (soles, uppers, and internal parts), clothing, and bodies of the two victims (Table 3). The vegetal component of the forensic traces was predominant in quantity over the inorganic one. A total of one hundred of specimens was sampled and traces were stored up in *capsules* of Petri and Eppendorf microtubes. In particular, for the sampling of the footwears, maps with the sampling areas of soil traces and plant remains were realized.

Sampling of the inorganic and organic component of the soils/sediments (known samples) and plants was carried out in the scene of events and usual sites frequented by the victims in the last days of their life (Table 3). Around one hundred of specimens of soils, around 500 g in weight, were sampled along a 500 m long transect stretched from the disappearance site to the scene of the events (known samples). Soils were stored in minigrip bags, linen bags, and glass bowls. Several freshwater samples were also collected from puddles, water stagnation, and tanks in the scene of the events and stored in glass bowls.

TABLE 3. Planning of the main activities carried out for the case work.

I PHASE
i. Preliminary inspection of the scene of events.
ii. Acquisition of the relevant documentation contained in the investigation dossier.
iii. Acquisition of existing scientific literature related to the topics of the case.
iv. Acquisition of data of investigative interest.

II PHASE
i. Acquisition of meteorological data of the study area from certified or public institutions.
ii. Acquisition of photos and videos recently taken and recorded via drone on the event site (taken by police, *carabinieri*, or firemen).
iii. Acquisition of the most recent orthophotos (DTM-Digital Terrain Model and DSM -Digital Surface Model) and satellite photos with the best resolution from certified or public institutions.
iv. Remote sensing aimed at geological and geopedological analysis.
v. Remote sensing aimed at searching for any burial/rudimentary concealment.

III PHASE
Inspections of the scene of events with dog handlers of cadaver dogs (for the search for clandestine grave).

IV PHASE
Collection of geological and botanical traces (unknown samples) on the victims (clothing and footwear) at laboratory.

V PHASE
i. Site inspections aimed at photographic and descriptive surveys of geological outcrops and vegetation with surveys on site with the use of GPS, aimed at reconstructing the state of the places, inherently the aspects to be investigated, and verifying what was observed indirectly with remote sensing.
ii. Site inspections aimed at crystallizing the state of the places through 3D reconstruction by means of laser scanner surveys (virtual models, Baldino *et al.* 2023; Somma *et al.* 2023a,b).
iii. Collection of samples of water/sediments/rocks/soils/vegetation (known samples) georeferenced with the use of GPS at the event scene and of investigative interest sites and sites attended by the victims a few days before the disappearance.
iv. Construction of a geodatabase of geological/geobotanical data, finds, paths, access routes through the use of dedicated software on the GIS platform (Geographical Information System) and other dedicated software.

VI PHASE
i. Analyses of geological and soil evidence from unknown and known samples at laboratory.
ii. Comparative and provenance studies.

VII PHASE
i. Data evaluation, answers to questions of the judicial authority, and conclusions.

5.3. GIS applications. A GIS-based map of the samples collected on the field was carried out for geological and botanical evidence. Data from field work and remote sensing activities (Table 3) were reported in digital maps dedicated to georeferenced vegetal and soil samples by GPS, geology, soils, geomorphology, and vegetation. These maps, elaborated in GIS platform using ArcGIS and QGIS, used as cartographic base, the most recent available imagery derived from air plan, drone, and satellite surveys, DTMs, DSMs, and detailed topographic maps.

5.4. Geological analytical methods. The laboratory analyses (Table 3) on unknown and known specimens of soils and sediments were performed in accordance with the "Best Practice Manual for the Forensic Comparison of Soil Traces" (Bourguignon *et al.* 2019). The activities consisted in:

i) Preliminary investigation and description,
ii) Analysis and determination of inorganic components and compositions,
iii) Comparison of results,
iv) Interpretation and assessment of the probative value of the comparison.

The examination of the inorganic component (composition and textural features of peculiar grains and grain associations, minerals, and microfossils) of the geological and soil samples was carried out on thousands of mm to μm sized particles for each sample. The analyses, as suggested by the national and international scientific community (Murray and Tedrow 1975; Sugita and Marumo 1996; Murray 2004a,b; Pye and Croft 2004; Morgan and Bull 2007; Ritz, Dawson, and Miller 2009; Di Maggio *et al.* 2013; Di Maggio and P. M. Barone 2017; Bourguignon *et al.* 2019; and references therein), carried out after the preparation of the samples and eventual physical separation into different granulometric sizes, were the following:

1) Granulometric analysis of the silty-sandy component of samples by means of laser diffraction granulometry and mechanical sieving.
2) Color analysis of fine fractions of samples by using the Munsell system.
3) Sedimentological analysis of the silty-sandy components of samples by means of stereomicroscope and petrographic microscope. These determinations were qualitative and quantitative by means of grain counting under microscope. In the forensic field *"counting the different types of particles is particularly important. The number of particles counted is much more useful than qualitative assessments"* (Murray 2004a). Sedimentological analyses consisted of:
   i. Clast typology determination (colour, luster, shape, relict *habitus*, coating, inclusions, opacity or any other noticeable characteristics),
   ii. Textural analysis - Clast rounding,
   iii. Textural analysis - Measurement of the grain size (inscribed diameter - Di of the clasts/particles),
   iv. Textural analysis - Measurement of the grain size (circumscribed diameter - Dc of the clasts),
   v. Textural analysis – Evaluation of the Particle Riley sphericity index (R).

4) Mineralogical and morphological analyses of the samples by means of petrographic microscope and Scanning Electron Microscope equipped with facility for Energy-Dispersive Spectroscopy (SEM-EDS).

5.5. Botanical analytical methods. The laboratory examination of the vegetal component of the soil traces was mainly carried out on mm to µm sized specimens of leaves, thorns, seeds, and algae sampled on the shoes, clothing, and bodies of the victims (unknown samples). In the present research, the terminology of some elements, as “thorns” was simplified using this term for the pointed plant structures, aware that the term “thorns” should have been used strictly for stem-derived structures, "spines" for other structures derived from leaves, petioles or stipules, and "prickle" for epidermal structures. In particular, a description of all the identified vegetal elements and plants was made at mesoscale in *situ* and microscale in laboratory (under the stereoscopic microscope). An extensive biometric analysis was made on thorns and seeds from the collected species in the scene of events and in the samples collected from the victims. A photographic atlas of the thorns and seeds of the main species found in the scene of the events was also realized. As regards the algae, it is noteworthy that identifying algae at the species level can reveal difficult. Taxonomic identifications of algae were based on the morphological characterization, based on the light microscopy. The morphological analyses regarded shape, size, color, whereas the cellular analyses regarded wall, unicellular, colonial, and multicellular organization observed at the light microscopy. Identified morphotypes and the peculiar associations of taxonomic entities were compared between unknown and known samples. The laboratory botanical activities consisted of:

1) macroscopic analysis of plants *in situ*,
2) morphological and biometric analysis of some plant elements (seeds, thorns, *etc.*) by means of stereomicroscope,
3) morphological analysis of microalgae by means of optical microscope,
4) morphological and biometric analysis of some plant elements (seeds, thorns, *etc.*) by means of SEM-EDX,
5) taxonomic identification of plants.

5.6. Instrumentations. The instruments and software used for geological and botanical analyses of traces and micro traces at laboratory of Forensic Geology of the University of Messina were:

i. stereoscopic optical microscope, Leica MZ 12 (magnifications from 8X to 100X);
ii. motorized stereoscopic optical microscope with reflected and transmitted polarized light, Stereo Discovery.V20 model - ZEISS (magnification from 3.8X to 75X with optical zoom - resolution 2.3 µm; magnification from 11.2X to 225X with optical zoom - resolution 0.8 µm; magnification from 26X to 530X with optical zoom - 0.4 µm resolution) with Zeiss tele camera and workstation;
iii. motorized petrographic optical microscope with reflected and transmitted polarized light, Imager.M2m model - ZEISS (objective magnification: 25X, 100X, 200X, 400X, 500X) with Zeiss tele camera and workstation;

iv. optical microscope for biological use, Laborlux 12 LEITZ (magnifications from 40X to 1000X (i.o.) with 12 MP digital camera, Apple Inc., USA;
v. SEM, QUANTA FEG 450 model - FEI, operating in low vacuum (chamber pressure of 50 Pa) at 20.00 kV with AMETEK EDS system and workstation;
vi. image analysis software for morphometry, AXIOVISION;
vii. laser diffraction granulometer, Mastersizer 2000 - Malvern Instruments with workstation;
viii. mechanical siever AS 200 control model – Retsch.

5.7. Comparative analyses. The degree of similarity (compatibility or comparability) between geological evidence is evaluated, in order to establish the possible origin of the traces from a same microenvironment or from a limited area where there are no significant variations of the characteristics under the compositional aspect in qualitative and quantitative terms. In other words, the evaluation of the degree of compatibility between geological evidence allows to establish the compatibility of the origin from the same microenvironment (Morgan and Bull 2007; Pye 2007; Ruffell and McKinley 2008; Di Maggio *et al.* 2013; Donnelly *et al.* 2021).

In comparative analyses, more parameters are compared, more solid will be the analytical results on which to express a reasoned technical opinion of compatibility. In the case work, the geological evidence was qualitatively and semi-quantitatively compared on the base of data related to sample mineralogical composition, type of inorganic particles, grain roundness and sphericity. Analogously, the botanical comparisons were based on data on taxonomy, morphology, color, and sizes of vascular plants and algae.

6. Results

6.1. Forensic Geology. The mineralogical analyses accomplished on the inorganic fraction, separated from the geological traces related to the unknown samples collected on the victims and their belongings, allowed to identify hyaline siliciclastic sands and silts mainly composed of mono-mineral grains of quartz, yellow to orange for the presence of hematite coatings, and minor light grey clay minerals (Figure 1). These latter in a few of samples were characterized by the presence of calcium phosphate. Minor grains consisting of opaque yellow ocher litoclasts of quartzarenites and microfossils (bentic *foraminifera*) were also identified. In addition, two peculiar particles collected on the sandals of one of the victims resulted composed of dolomite. Analogous results were obtained from the sandy and silty soils (known samples) collected on the sites of the events where the specimens resulted to be composed of the same siliciclastic mineral assemblage above reported. Specimens of clays with traces of calcium phosphate and pinkish dolostones of anthropogenic provenance were identified in one locality of the scene and in the clasts of a dirty path, respectively.

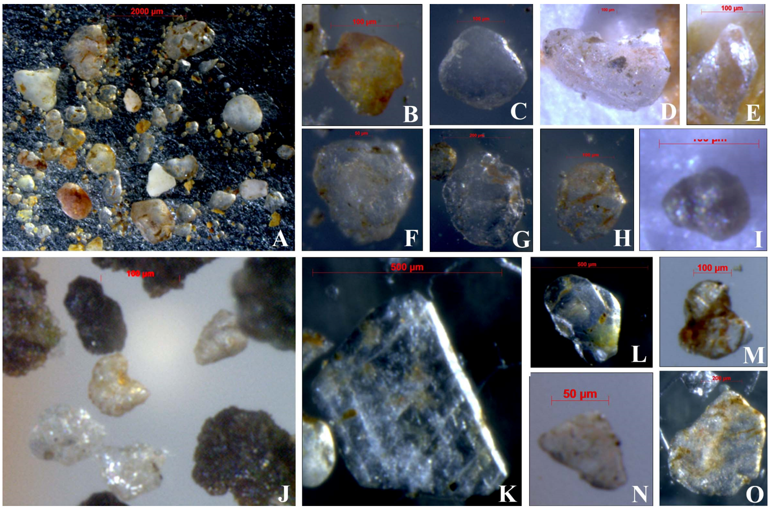

FIGURE 1. Inorganic component in the questioned samples of soil collected on the two victims. A) Quartz grains in the soil traces collected on the T-shirt of victim 1. B-H) Different types of grains classified on the base of colour, luster, shape in the belongings of victim 1. I) Specimen of benthic foraminifer collected in the belongings of victim 1. J) Quartz grains in the soil traces collected in the sandals of victim 2. K) Grain of feldspar collected in the belongings of victim 2. L-O) Different types of grains classified on the base of colour, luster, shape in the belongings of victim 2.

Notwithstanding the mineralogical homogeneity of the samples, the observations under stereomicroscopy allowed to identify in unknown and known samples seven different classes of grains on the base of the different luster, coating, color, shape, *habitus*, roundness, and sphericity. The different particles were classified in the different classes and quantitatively counted for each different grain sizes in each specimen. About two thousand of sandy grains from the unknown and known samples were analysed.

6.2. Forensic Botany. The vegetal fraction separated from the geological traces related to the unknown samples collected on the victims resulted to be composed of plant fragments or entire elements of branches, twigs, leaves, thorns, *capsules*, fruits, seeds, pollen, herbaceous fragments, wood, vegetable debris, decomposing organic material (*humus*), and microalgal assemblages (including diatoms) (Figure 2). The main species of terrestrial plants (Morabito, Mondello, and Somma 2023) identified in the vegetal component of the forensic unknown samples were (Figure 2):

i. *Erica arborea* (leaves, *capsules*, seeds Figure 2B),
ii. *Quercus suber* (leaves, flowers, seeds),
iii. *Olea europaea* (leaves, seeds),
iv. *Cistus monspeliensis* (leaves, seeds, *capsules*, *etc*.),
v. *Pistacia lentiscus* (leaves, seeds),

vi. *Myrtus communis* (leaves, seeds),
vii. *Cytisus infestus* (branches, legume, thorns),
viii. *Smilax aspera* (leaves, thorns),
ix. *Rosa sempervirens* (thorns, Figure 2C),
x. *Rubus ulmifolius* (thorns),
xi. *Rosacea Amygdaloidea* (thorns),
xii. *Cynara cardunculus* (thorns).

Thorns and seeds were the most abundant vegetal component sampled on bodies, clothing, and shoes of both victims. Over 522 seeds of *Erica arborea* and 81 thorns ascribable to *Rosa sempervirens, Rubus ulmifolius, Rosacea Amygdaloidea, Cynara cardunculus, Cytisus infestus*, and *Smilax aspera* were found in the shoes of victim 1, mostly inside the shoes and planted on the soles, respectively (Figure 2). Sixteen thorns ascribable to *Rosa sempervirens* or *Rubus ulmifolius, Cynara cardunculus, Cytisus infestus*, and *Smilax aspera* were found planted on the soles of the sandals of victim 2 (Somma 2023b).

Remnants of a mm-sized microalgal aggregate (Figure 2D-F) was identified on the soles of the victim 1's shoes. Five distinct species of green algae *(Chlorophyta)*, one morphotype of blue algae *(Cyanophyta)*, and diatoms *(Ochrophyta)* were recognized in the aggregate (Morabito and Somma 2023).

The above reported species of terrestrial plants were found also in the sites of the events where different macro-areas with different botanical characteristics were distinguished during field and remote sensing work. Analogously, the microalgal association was also recognized in wet soils found in the sites of the events.

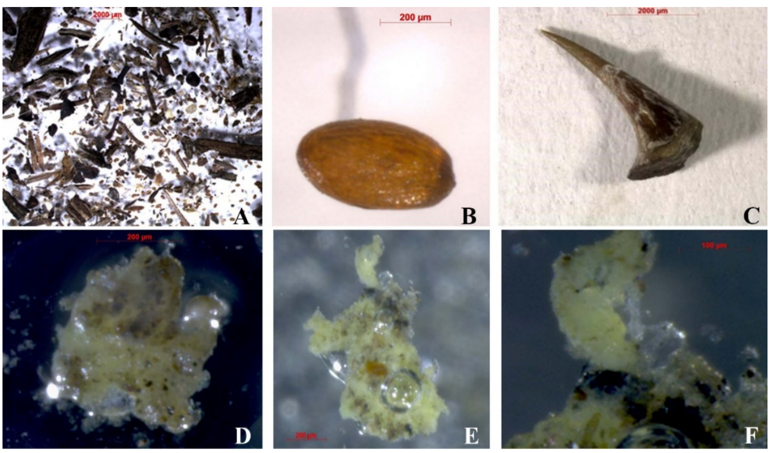

FIGURE 2. Vegetal component in the questioned samples of soil collected on the victim 1 belongings. A) Abundant organic rich soil with fragments of branches, seeds, thorns, and *humus* matter collected on the internal part of one shoe. B) Detail of a specimen of seed of *Erica arborea* (Figure A). C) Detail of a thorn of *Rosa sempervirens* (Figure A). D-F) Freshwater algae dispersed in water and collected on the sole of the shoes.

7. Discussion and conclusions

The results of the geological and botanical characterization accomplished on the traces collected on the victims and their belongings (unknown samples) and soils and plants sampled on the scene of events (known samples), allowed to ascertain with a high degree of compatibility as the source of the unknown samples could derive from environments with characteristics similar to those found in the scene of events, suggesting a same common origin for the analysed unknown and known specimens.

Peculiar minerals (calcium phosphate rich clays and dolostones), very abundant vegetal particles (thorns and seeds of *Erica arborea*), and algae associations were particularly useful in linking the victims to the scene of events.

The results of the comparative analyses provided fundamental info-investigative data useful for establishing the *pre-mortem* active presence of the victims on the scene. Furthermore, the most significant positive matches found allowed reconstructing a very detailed walking carried out by the two victims on the event site in the hours immediately preceding their death. These implications were of paramount importance for the judicial system in the solution of this criminal case.

The careful examination of mineral composition, textural features as well as of the peculiar assemblages of inorganic and vegetal materials from unknown and known specimens carried out in the case work revealed to be able to provide very strong geological and botanical evidence for supporting criminal investigations. These robust results were achieved by the experts involved in long time-consuming and careful activities and examinations.

Furthermore, the geological and botanical investigation carried out demonstrated as the analyses of the relationships ascertained between the victims and the surrounding environment could also support the coroner's decision on the manner of death and facilitating the understanding of the event dynamics.

Notwithstanding these encouraging results, in the Italian police criminal investigation, the analysis of geological and botanical origin traces rarely occurs. The great potentiality of these studies was previously provided by the geologist Prof. Gianni Lombardi and the botanist Prof. Valerio Giacomini for the criminal investigation related to the homicide of the statesman, Aldo Moro occurred in the 1978 (Lombardi 1999). This mutual and effective approach, based on the application of both forensic geology and botany to serious crimes, was also demonstrated for war crimes occurred in Bosnia (A. G. Brown 2006). Nowadays, the Italian experts in Forensic Geology and Botany are not usually enrolled by the police institutes and nobody is actually present among the police criminalistic investigators intervening at the crime scene; this lack may be due to the lack of specific university courses devoted to these disciplines of criminalistics. Another criticism actually occurring in most of the Italian crime scenes may be related to the possible dispersion of geological and botanical evidence. It must be highlighted that during the removal of the cadaver from the scene, the insertion in the body bag and the subsequent transfer to the morgue shelter and on the autopsy table, may be difficult preserve intact the possible inorganic and organic (vegetal) traces or micro-traces. Consequently, it is very high the probability that the inorganic and organic traces and micro traces, almost always present on the cadaver remains found in the countryside, could be dispersed, especially if not recognized by experts in geology and botany.

On the basis of the above and the personal experience of some of the Authors (R.S., F.M., M.M.), it is highlighted that it should be desirable to:

i. further implement initiatives on Forensic Geology and Botany, provided by the Messina University until the 2015, and promote the establishment of degree and postgraduate courses in the topics of Forensic Geology (Somma 2022) and Botany;
ii. promote the presence of forensic geologists and botanists among the experts of the police forensic teams intervening at the crime scene in rural areas before the removal of the body and in the laboratory for trace analyses and of the defence scientific investigation teams;
iii. develop a forensic protocol envisaging all possible technical procedures /operations to accurately apply on the crime or event scene to preserve and sample inorganic and organic materials;
iv. strengthen greater interaction and collaboration between forensic geologists, botanists, experts, and coroners at the crime scene, to arrange all the activities aimed at preserving the traces as far as possible, even during necropsy operations; this collaboration should be realized arranging a forensic medicine protocol envisaging all possible technical procedures / operations to apply from the crime scene to the autopsy table, in order to preserve the inorganic and organic (vegetal) traces potentially present and often invisible to the naked eye.

Author Contributions

Conceptualization, R.S., M.M.; methodology R.S., M.M.; validation, R.S., M.M.; formal analysis, R.S., M.M.; investigation, R.S., M.M.; resources, R.S., M.M.; data curation, R.S., M.M., F.M., M.C., F.C.; writing original draft preparation, R.S., M.M.; writing review and editing, R.S., M.M.; visualization, R.S., M.M.; supervision, R.S., M.M. All authors have read and agreed to the published version of the manuscript.

Competing interests

The authors declare no conflict of interest.

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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 18 March 2023; published online 12 September 2023