

## FORENSIC GEOLOGY APPLIED TO CRIMINAL INVESTIGATION: A CASE REPORT

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**ABSTRACT.** The present research was devoted to the geological study of two forensic samples of geological evidence collected on the belongings of a victim of gun shooting, found in a rural area of the countryside in southern Italy. Geological analyses on these granular samples were requested in order to ascertain the possible provenance of the evidence. The results of mineralogical, sedimentological, and micropalaeontological investigation on the clasts/grains indicated that the geological evidence presumably originated from an area where outcrops of sedimentary, metamorphic, and volcanic rocks were present. The petrographic characters of the clasts made up of metamorphic rocks were compatible with the crystalline basements of the Calabria-Peloritani Arc (southern Italy). An important constraint in the specimens was the presence of very peculiar grains of volcanic rocks compatible with those of pyroclastic products of the Mount Etna. Another important constraint was represented by the finding of benthic foraminifers, released by a marly-clayey aggregate. These foraminifera are common in grey-blue clays passing laterally to the calcareous sands cropping out in the Messina province along the Tyrrhenian and the Ionian coasts. In conclusion, the studied geological evidence, notwithstanding one of the samples was of mixed origin, could geographically derive from an area of the Calabria-Peloritani Arc. In particular the material found in one of the samples could derive from an area not too far from the coast and where Etna volcano ashes could also arrive and deposit.

### 1. Introduction

When a crime occurs outdoor in the countryside, the contact of objects, such as shoes, boots, and clothes of a subject (victim or perpetrator), with geological and soil evidence present at the crime scene may determine a transfer of traces and subsequent storage of such materials from the sites to the objects. Known in forensic sciences as principle of exchange of Locard (Picozzi and Intini 2009; Saferstein 2017), this transfer is of fundamental importance in the forensic inferences, explaining the reason for which a determined trace found on a subject may be the evidence for linking the actors between them or to the crime scene. Sediments and soils are complex systems studied by forensic geologists and soil scientists. Forensic geology (or geoforensics or forensic geosciences) is a branch of

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criminalistics which applies principles and methods of 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; Pye 2005; Ruffell and McKinley 2005; McKinley and Ruffell 2007; Morgan and Bull 2007; Pye 2007; Ritz, Dawson, and Miller 2008; Fitzpatrick, Raven, and Forrester 2009; Pirrie 2009; Ruffell and McKinley 2009; Ruffell and Kulesa 2009; Ruffell 2010; Pirrie, Ruffell, and Dawson 2013; Di Maggio *et al.* 2014; Ruffell and McKinley 2014; Pirrie, Dawson, and Graham 2017; Sagripanti *et al.* 2017; Werner *et al.* 2019; Fitzpatrick and Donnelly 2021; Somma 2022; Somma 2023a,b,c). Main geoscientific disciplines usually involved in crime investigation are mineralogy (Murray 2004b; Pirrie *et al.* 2004; Ruffell and Wiltshire 2004; Bull *et al.* 2005; Bull and Morgan 2006; Ruffell and McKinley 2009; Bourguignon *et al.* 2019), sedimentology, palaeontology (Riding 2021), geochemistry (Morgan and Bull 2006; Spoto, Somma, and Crea 2021), geophysics (Davenport *et al.* 1990; Ruffell and Parker 2021), remote sensing (Davenport *et al.* 1990; Doyle and Bennett 1997; Davenport 2001; Ruffell 2002; Ruffell and Wiltshire 2004; Ruffell 2005b; Brown 2006; Herrmann and Devlin 2008; Wolff and Asche 2009; Pringle and Jervis 2010; Elmes, Roedl, and Conley 2014; Ruffell and McAllister 2015; Bunch, Kim, and Brunelli 2017), hydrogeology (Ruffell *et al.* 2017), environmental geology (Ruffell and Kulesa 2009; Ruffell 2013), and applied geology. Moreover, certain disciplines, such as geography may fall in a dominion common between different humanistic, sociological, psychological, criminological, and biomedical matters, where this discipline is applied for the geographical and criminal profiling of serial crimes (Hirschfield and Bowers 2001; Canter 2005; Douglas *et al.* 2013; Kamaluddin *et al.* 2021; Somma 2022; Somma 2023a; Somma and Costa 2023). Crimes for which forensic geologists are usually uncharged in order to study geological and soil evidence are commonly homicides (Lombardi 1999), kidnappings, corpse concealments in clandestine graves and searches (France *et al.* 1997; Ruffell and Wilson 1998; Ruffell and Wiltshire 2004; Ruffell 2005a; Manhein, Listi, and Leitner 2006; Salsarola and Cattaneo 2009; Harrison 2011; Larson, Vass, and Wise 2011; Pringle *et al.* 2012; Ruffell and Schneck 2017; López Batista, López, and Batista 2018; Somma *et al.* 2018; Rocke, Ruffell, and Donnelly 2021; Rocke and Ruffell 2022; Marra 2023; Somma, Sutton, and Byrd 2023; Tagliabue *et al.* 2023), frauds and fakes regarding fossils and gemstones (Ruffell, Majury, and Brooks 2012; Ruffell and Schneck 2017; Marra, Di Silvestro, and Somma 2023; Spoto 2023; Spoto, Barone, and Somma 2023), environmental crimes (Oivanki 1996; Ritz, Dawson, and Miller 2008; Ruffell and Dawson 2009; Ruffell and Kulesa 2009; Pirrie, Ruffell, and Dawson 2013; Ruffell *et al.* 2018; Ruffell and Barry 2021; Somma and Costa 2022; Somma *et al.* 2023d). In most crimes the multidisciplinary approach in team of experts in botany (Morabito, Mondello, and Somma 2023; Morabito and Somma 2023), entomology (Byrd and Sutton 2023; Somma, Sutton, and Byrd 2023), and engineering (Baldino *et al.* 2023; Somma *et al.* 2023a,b,c,d) may be crucial for a successful investigation. Forensic soils are composed of inorganic, organic, and anthropogenic (glass, plastic, hairs) components (Murray 2004b; Ruffell and Kulesa 2009; Di Maggio *et al.* 2014). Their origin is due to geopedological processes, which transform original igneous, metamorphic, and sedimentary rocks (parent rocks) exposed on the continental surface in soils (Murray 2004b). The soil can be considered as a residual sedimentary rock made up of inorganic and organic matter, in varying proportions. Soils deriving from sedimentary rocks have a high probability to bear macro-, micro-, and

nannofossils. Consequently, fossils, being sometimes also rare or unusual, may represent important forensic diagnostic elements for defining the provenance and circumscribing investigation on a certain geographical area or excluding it (Murray 2004b; Ruffell and Dawson 2009; Di Maggio *et al.* 2014). Previous studies of outdoor crime scenes showed that foraminifers may help in matching the crime actors to the places (Riding 2021 and references therein). The critical attributes of foraminifera are their small size and great abundance even in few grams of samples. Additionally, the minerals forming the inorganic component of the soils may provide important information. Minerals can be primary (*e.g.* deriving from the physical disaggregation of the underlying parent rock) or secondary (deriving from weathering of primary minerals) and are distinguished between heavy and light minerals (Di Maggio *et al.* 2014). In areas characterized by outcrops of silicate rocks, as in most of the cases involving metamorphic and magmatic rocks or sedimentary siliciclastic deposits, the sandy and silty soil primary minerals, are mainly represented by monomineral clasts of quartz, feldspars, biotite, muscovite, pyroxenes, amphiboles, and olivine or polymineral aggregates of these species. The secondary minerals, usually present as clayey grains, consist of clay minerals (*i.e.* illite, montmorillonite, kaolinite, pyrophyllite), variable soluble minerals (calcite, gypsum), oxides and hydrous oxides of iron and aluminium (*e.g.* goethite, hematite), and amorphous aluminosilicates (*e.g.* allophone and imogolite). The organic component of soils is formed by remains of microorganisms (bacteria, fungi, *etc.*), animals (mainly insects, other invertebrates, *etc.*), plants (roots, stems, buds, seeds, fruits, leaves, algae; Morabito and Somma 2023; Morabito, Mondello, and Somma 2023), and humus (Di Maggio *et al.* 2014). The latter, characterized by the classical dark colour, results from biochemical reactions transforming and degrading the remains of organic matter of biological origin. Forensic soils, unlike natural soils, can also contain anthropogenically introduced products, such as fibres, animal or human hairs, and fragments of materials such as glass, rubber, metals, paint, asphalt, and plastics (Di Maggio *et al.* 2014). In the past, geological analyses provided useful and crucial forensic evidence for solving serious crimes, as in the case of the kidnapping and homicide of Aldo Moro in 1978. In that case work, Lombardi (1999) found on the belongings of the victim 1 gram of siliciclastic sands with actual organisms and fossils (some planktonic and benthonic foraminifers and other bioclasts). The mineralogical, sedimentological, and palaeontological characteristics of these sands allowed to establish the provenance of the sample, ascribing it to beach sands of the Lazio coast (Lombardi 1999). Such geological investigations have recently been ruled by the protocols reported in the Best Practise Manual BPM (Bourguignon *et al.* 2019) recently proposed by the Animal, Plant and Soil Traces APST expert working group of the European Network of Forensic Science Institutes (ENFSI).

The present research is devoted to the geological study of forensic samples of soils. Comparative analyses on these specimens were requested. The results of mineralogical, sedimentological, and micropalaeontological investigation were reported and discussed in the present paper.

## 2. Materials and methods

Geological analyses, based on determination of color (Sugita and Marumo 1996; Somma *et al.* 2023d), grain size distribution, textural, mineralogical, and palaeontological features

(Murray 2004b; Di Maggio *et al.* 2014; Bourguignon *et al.* 2019), were accomplished on two forensic soil samples (samples A and B). Usually, the initial forensic analyses are related to non-destructive activities, such as the visual inspection of the sample at mesoscale (by means a magnifying glass), followed by more detailed microscopic optical observations and when necessary, also by specific non-destructive and destructive analyses. The general characteristics of the studied samples, such as organic matter content, structure, and texture were firstly determined in the specimen, as it was, using a stereo microscope (Discovery.V20, Zeiss, laboratory of forensic geology) provided of a workstation with image analysis software. During this preliminary analysis, great attention was devoted to the examination and identification of both organic (in particular plant remains) and inorganic components. Any peculiar particle was recorded and sub-sampled for further specific analyses of specialists. After treatment of the samples, being the size of the samples adequate, grain size was determined by means of dry mechanical sieving using small-size sieves with 2,000, 1,000, 500, 250, 125, 62.5  $\mu\text{m}$  square meshes. The color was determined by means of the comparative soil-charts of Munsell. Textural, morphological, morphoscopic, and morphometric analyses of the inorganic components (minerals and fossils) and of any anthropogenic element of investigative interest (glass, plastic, hairs) were carried out for each grain size under stereomicroscope. Peculiar grain and fossil specimens were picked and sub-sampled under the stereomicroscope. Fossils were determined at the species levels. Detailed characterization of some mineral particles was obtained, using a system SEM-EDS (Scanning Electron Microscope - Energy Dispersive Spectrometry; Pirrie *et al.* 2004; Bull and Morgan 2005, 2006). The instrument used was the SEM INSPECT-EDS (FEI Inspecta). The SEM images provided by an electronic microscope are produced by electrons that, passing through the scanning system, are deflected by magnetic fields that allow to scan the sample surface. The mineralogy of the inorganic component was also determined by means of XRPD (X-Ray Powder Diffraction) (Ruffell and Wiltshire 2004). The sub-samples were analysed after manual quartering and grinding in agate mortar. The instrument used for XRPD analyses was the D2-Phaser diffractometer (Bruker, laboratory of forensic geology of the Messina University). The XRPD technique is based on the diffraction pattern obtained by reflections of X-rays on the crystalline planes of the investigated material.

### 3. Case work

A corpse of a man with injuries caused by firearms was found in a rural area of the countryside in southern Italy, away from dwellings. Traces of cocaine were found inside the pockets of his clothing. The victim was already known to police forces for his criminal record related to drug dealing. Two types of soil traces were collected by law enforcement officers (almost ten years ago) on the footwear soles (sample A) and inside the pockets of the clothing (sample B) of the victim. The questioned samples were committed to one of the authors (R.S.) for investigation in order to ascertain the compatibility degree and provenance (Figure 1). No further control samples or investigative informations were provided.

**3.1. Sample A.** Sample A (weight: 11.30 g) appeared heterogeneous (Figure 1 A), mostly formed by different types of inorganic matter (mineral grains, Figure 2) with a low content in organic component (little stems, roots, seeds, and leaves) and anthropogenic particles (fibers, plastic fragments, cm-long transparent plastic cylinders broken on one side, colored

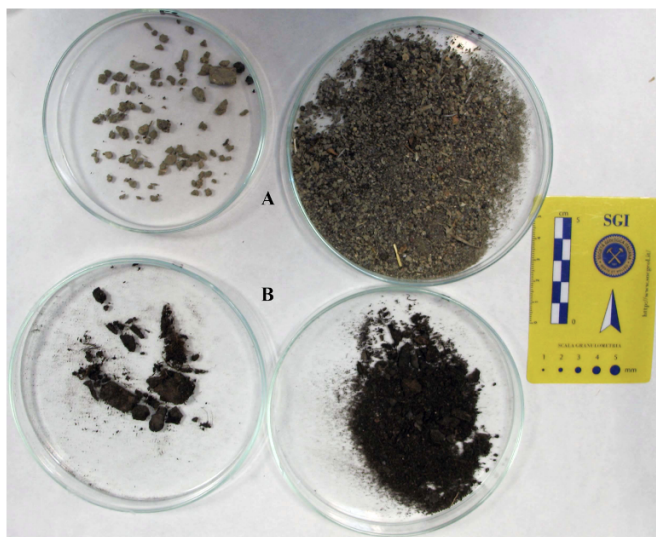


FIGURE 1. Photography showing questioned samples A and B contained in glass capsules of Petri.

glass, Figure 2 C). Inorganic component was represented by mono- and polymineral silicate clasts (Figure 2 A), black amorphous grains (Figure 2 B) showing a sandy to silty texture with minor pebbly particles, and marly aggregates. The main mono- and polymineral clasts, recognized under stereomicroscope for their evident mineral habitus, cleavage, luster, and color (Murray 2004b), were quartz, white mica, feldspar, and black mica (monomineral clasts) and sericite phyllites (Figure 2 A) and gneiss (polymineral clasts).

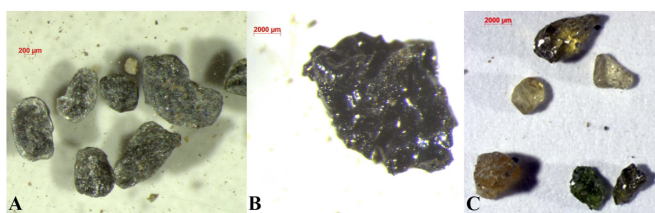


FIGURE 2. Inorganic and anthropogenic components of sample A observed under stereomicroscope. A) Rounded clasts made up of sericite phyllites. B) Grain of volcanic glass. C) Anthropogenic particles represented by mm-sized colored glass fragments with typical conchoidal-type fractures (olive green, green, amber, hyaline in colour).

The mm-sized amorphous (glassy) black grains showed typical conchoidal-type fractures (Figures 2B, 3) and porous structure with spherical to sub-spherical cavities. The SEM images allowed to better define this porous structure. Pores were from spherical to ellipsoidal.

The XRD analysis of these grains indicated the occurrence of anorthite, forsterite-rich olivine, and augite (Figure 4). All these features suggested that the black amorphous grains were of volcanic origin with a composition typical of basalts.

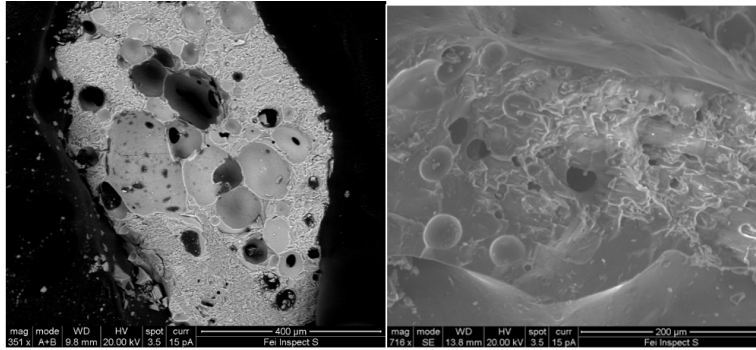


FIGURE 3. SEM images of a black glassy grain showing the porous texture (Sub-sample A).

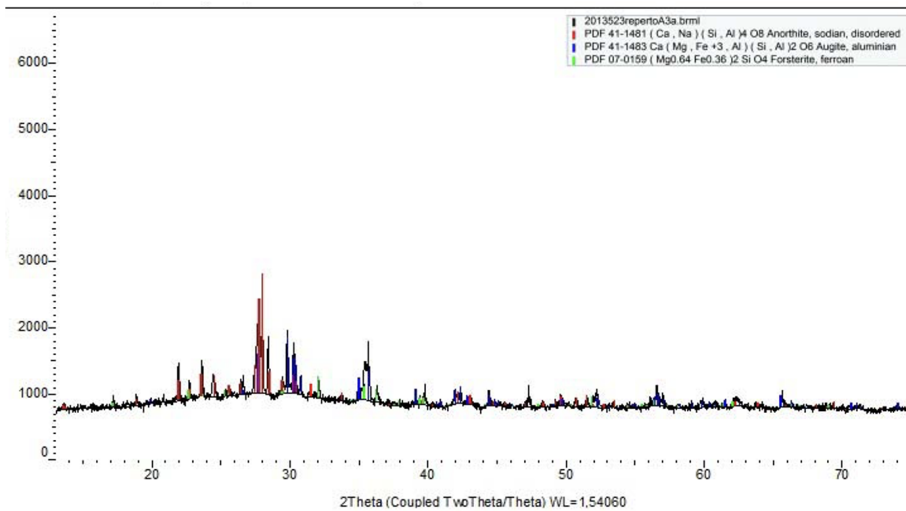


FIGURE 4. Diffractogram of the black glassy grain (Sub-sample A).

Most of the inorganic component in sample A was formed by light grey fine-grained siliciclastic aggregates. The matrix of these aggregates, observed in dried conditions, showed a light grey Munsell color 2.5Y 7/1, and being composed of both carbonates (the contact with dilute 10% HCl produced a violent effervescence) and clays, resulted to be a marly sediment. This composition was confirmed by XRPD analyses that allowed

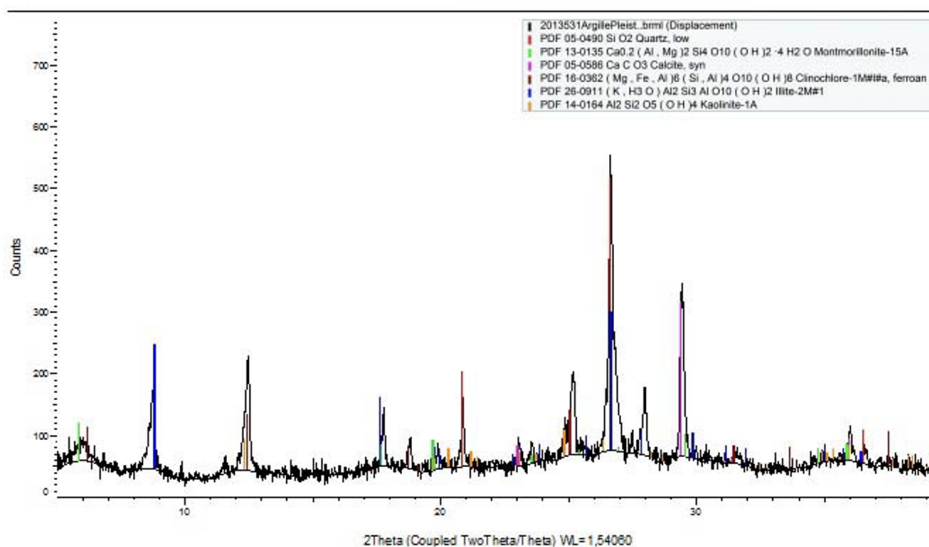


FIGURE 5. Diffractogram of the grey-blue marly aggregates (sub-sample A).

also to ascertain an assemblage of clay minerals, in oriented specimen, made up of illite, montmorillonite, kaolinite, clinocllore, quartz, and calcite (Figure 5).

One of these aggregates showed a peculiar shape, like a truncated pyramid ( $h = 6$  mm) with rectangular base (12 mm x 8 mm; Figure 6). This released tens of fossils.

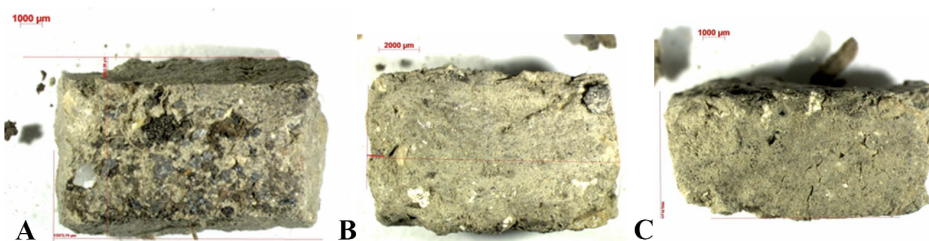


FIGURE 6. Different views of one marly aggregate of sample A observed under stereomicroscope. This aggregate released the main part of studied foraminifera.

Special attention was paid to the study of this fossiliferous contents mainly consisting in foraminifera. These organisms are single-celled protozoa, living in brackish and marine environments from near shore to deep sea. In the sample, tens of benthic foraminifera, smaller than 2 mm in size, were identified. *Amphistegina lessonii* d'Orbigny (Figure 7) was the most common species found, followed in abundance by *Elphidium crispum* (Linnaeus, Figures 7, 8 A), and *Planulina ariminensis* d'Orbigny (Figure 8 B). One specimen assigned to *Hyalinea balthica* (Schröter) and some globigerinids (planktonic foraminifera) were also recognized.

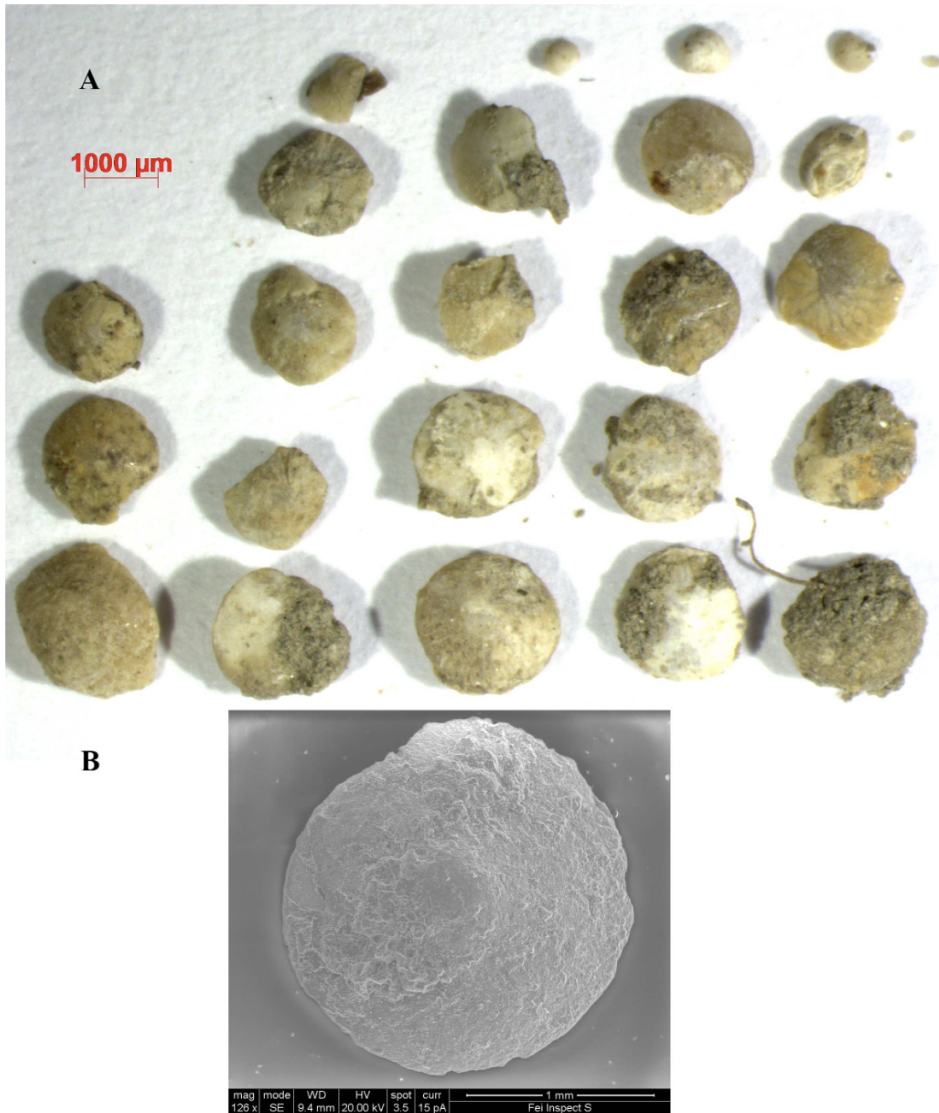


FIGURE 7. Foraminifera of sample A observed under stereomicroscope (A) and SEM (B). A) Plate of benthic foraminifera: *Amphistegina lessonii* d'Orbigny and *Elphidium crispum* (Linnaeus). B) SEM image of a specimen of *Amphistegina lessonii* d'Orbigny.

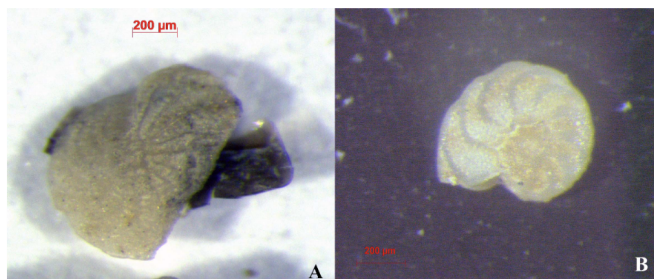


FIGURE 8. Foraminifers of sample A observed under stereomicroscope. A) Specimen of *Elphidium crispum* (Linnaeus). B) Specimen of *Planulina ariminensis* d'Orbigny.

**3.2. Sample B.** The sample B (weight: 2.57 g), observed in dried conditions, showed a dark brown Munsell color 7.5YR 3/2 (Figures 1, 9 A). The specimen appeared homogenous, as mostly formed by dark organic matter with a very low content in natural inorganic component (Figure 9 A). A portion of the sample was also composed of anthropogenic components characterized by cm-long synthetic-colored fibres (blue, transparent, red) and brown wavy hairs. Soil structure was characterized by mm- to cm-wide aggregates of vegetal particles (Figure 9 A). Vegetal remains were mainly formed by little roots. Some seeds, fungal hyphae, and organic tissues, were also present. The inorganic grains were represented by primary monomineral and polymineral clasts showing a sandy to silty texture with some fine to medium aggregates. The stereomicroscopic observation allowed to recognize the monomineral and polymineral characters of most of the clasts. Monomineral clasts were represented (in order of abundance) by muscovite, quartz, feldspar, and biotite, whereas the main polymineral clasts were characterized by mineral assemblages of quartz+feldspar+muscovite+biotite (pegmatite, Figure 9B) and quartz+feldspar+biotite (biotite micaschist, Figure 9 C). The bulk composition of Sample B, analysed by XRPD, confirmed optical observations and in particular allowed to ascribe feldspars to anorthite (Figure 10).

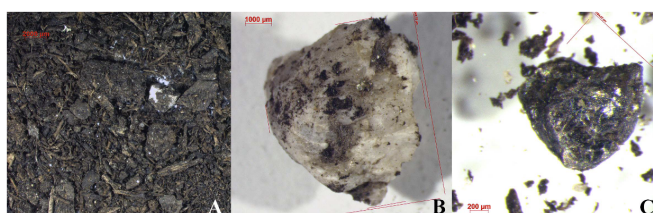


FIGURE 9. Sample B observed under stereomicroscope. A) Abundant organic matter. B) Clast formed of pegmatite showing light siliciclastic minerals and micas. C) Clast composed of biotite mica schist.

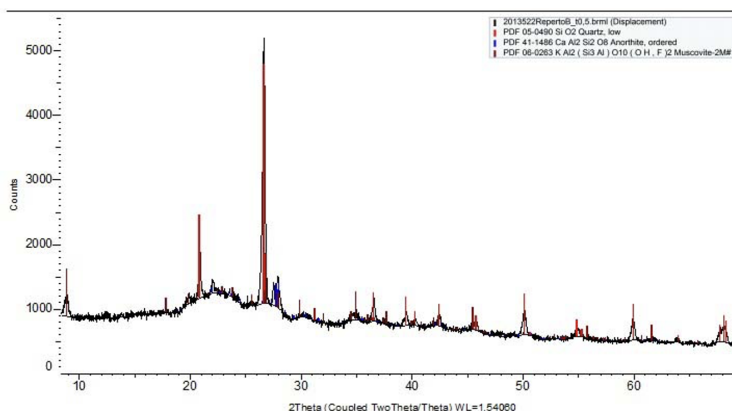


FIGURE 10. Diffractogram of the inorganic component of sample B.

#### 4. Discussion

In the presented case work, two specimens of forensic soils were carefully examined in order to ascertain their provenance.

**4.1. Sample A.** The specimen showed a significant compositional heterogeneity, due to the simultaneous presence of metamorphic rock clasts, volcanic particles, and sedimentary marly aggregated with foraminifers. Such heterogeneity was indicative of a process of mixing of different inorganic materials (Murray 2004b; Di Maggio *et al.* 2014), probably transferred to the footwear soles in different times and from different sites. In such cases, unfortunately the consequent forensic information, inferences, and use in a court are compromised (Murray 2004a,b). To avoid such problematics, it is strongly recommended that the collection of the geological and soil evidence from questioned samples, such as in this case work, is carried out by forensic geologists. These experts, being trained to detect different traces in the inspected items and to carefully collect and map them with dedicated software (ArcGIS, QGIS, vectorial software), are able to keep the different traces separate, to preserve them in distinct sub-samples and to detect possible microstratigraphy and polarity. Conscious of the fact that this evidence, being a mixed sample, cannot be used in a court, however some geological considerations may be expressed on the different types of grains detected.

**4.1.1. Clasts of metamorphic rocks.** The primary monomineral clasts (quartz, muscovite, feldspar, biotite) found were not particularly significant, being common minerals in most of the siliciclastic soils. More interesting under a forensic point of view were the studied polymineral grains. They consisted of sericite phyllites and gneiss, typical metamorphic rocks of the Mediterranean area (Calabria-Peloritani Arc, Alps, Betic Cordillera, Rif, Kabylies, and Corsica; Somma *et al.* 2013). Consequently, at the scale of southern Italy, crystalline rocks crop out exclusively in the area comprised between the Pollino line in Calabria (Iannace *et al.* 2007) and the Longi-Taormina Line in north-eastern Sicily (*i.e.* Calabria-Peloritani Arc, Aldega *et al.* 2011). The clasts of gneiss and phyllites of sample

A could derive exclusively from the Calabria-Peloritani Arc, and consequently most of the territory of Sicily (southern and central-western Sicily) can be excluded. Under a geological point of view, these polymineral grains may derive from weathering of high (gneiss) to low grade (phyllites) metamorphic rocks belonging to the different tectonic units of the Peloritani Chain and Aspromonte Massif. Nevertheless, it cannot be completely excluded that polymineral grains derived from weathering of metamorphic rocks, present as “cannibalized” clasts, in terrigenous sedimentary rocks. Such sedimentary rocks, *i.e.* granular sediments formed by clasts of metamorphic rock, are widespread in the Peloritani Chain and Aspromonte Massif.

**4.1.2. Volcanic clasts.** The black amorphous grains resulted to be of volcanic origin. Among the black grains, there were some of them completely glassy, others showed a crystalline texture typical of volcanic rocks (basalt). Both types of black grains were compatible with pyroclastic products (volcanic ash and lapilli) presumably related to the volcanic activity of Mount Etna.

**4.1.3. Marly aggregates and foraminifers.** The grey marly aggregates consisted of marls composed of a mixture of calcite and clay minerals, such as illite and montmorillonite with minor kaolinite. A characteristic feature associated with these aggregates was the abundant occurrence of fossils (benthic and planktonic foraminifera). Particularly, tens of specimens of benthic foraminifers, mm-sized, were found. Among them it is worth of note the presence of *Amphistegina lessonii* d’Orbigny, *Elphidium crispum* Linnaeus, *Hyalinea baltica* Schröter and *Planulina ariminensis* d’Orbigny). *Amphistegina lessonii* and *Elphidium crispum* gave some important clues. They are long-lived species present in sedimentary rocks, ranging in age from the Miocene to the present. They live in shallow marine environments (shelf, reef, and lagoon) and are contained in rocks that have originally deposited in such environments. *Amphistegina lessonii* and *Elphidium crispum* are common in infralittoral upper Pliocene-middle Pleistocene calcarenites and sands (Di Stefano and Longhitano 2009). *Hyalinea balthica* is a marker species, which also gives information on the age of the original associated parent rock. It first appears in the Early Pleistocene (Emilian stage) and is indicative of sediments deposited in shelf-upper bathyal environment. Therefore, the occurrence of these species is useful to look for sedimentary rocks, which may contain this biomarker. It is often present in lower to middle Pleistocene grey-blue clays (*e.g.* Spadafora Fm) passing laterally to the calcareous sands, cropping out in the Messina province along the Tyrrhenian and the Ionian slope. The comparisons of the mineral composition and color of the marly aggregates of Sample A and the lower to middle Pleistocene grey-blue clays and marls indicated that the marly aggregates were compatible with the grey-blue clays. Consequently, the marly aggregates can derive from the lower to middle Pleistocene grey-blue clays and marls. The contact of the boots with a wet topsoil on these lower to middle Pleistocene deposits determined an easy transfer of these sediments to the footwears. A water content in the marls made easy to storage foraminifers, deriving from the contact of the boot soles with a topsoil lying on presumably upper Pliocene-middle Pleistocene calcareous sandy sediments. In particular, it is necessary to underline that the polarity of the aggregate with truncated pyramid shape unfortunately was not annotated by the sample collector. This information and microstratigraphy of the material could have provided precious data on the relative chronology of the material transfer.

**4.2. Sample B.** The main component of sample B was the organic matter presence. The latter indicated that the soil could derive from environments showing a topsoil formed by slightly decomposed and abundant organic litter (horizon Oi) such as a wood. The clasts of pegmatites and biotite mica schists found in sample B suggested a provenance from the Calabria-Peloritani Arc, as for the sample A.

## 5. Conclusions

The presented case work would suggest that the different inorganic particles found in the mixed heterogenous soil (sample A) and the homogenous soil (sample B) originated from a geological area where outcrops of sedimentary, metamorphic, and volcanic rocks are present in the territory. An important constraint was the presence of very peculiar volcanic clasts. Aware that the specimen underwent a mixing of the materials, sample A could be deriving from different outcrops of the Calabria-Peloritani Arc, in an area not too far from the coast and where Etna volcano volcanic ashes could also fall. The transfer of the soil of sample B into the pockets of the jacket of the victim could be indicative of a transport of the corpse due to a drag on the ground from the crime scene to the car or up to the site of finding. Control samples from crime scene and sites of investigative interest and a proper collection of the samples A could have helped the authors to better reconstruct past events and dynamics.

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