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AN INTRODUCTION TO FORENSIC GEOSCIENCES

Sebastiano Ettore Spoto [a*], Serena Barone [b], Roberta Somma [ac]

Abstract. In the current criminalistic scenario, experts face many challenges, including huge amounts of data, lack of time, tiny pieces of evidence, chaotic and complex crime scenes, complicated and time-consuming procedures, inadequate laboratory structures, and sometimes insufficient knowledge, which may lead to failure of investigation or to expire the periods of prescription. This paper briefly overviews the added value in the Forensic Science and Criminal Investigation scenario of some key geoscientific disciplines applied to forensic fields, such as geochemistry, geophysics, geopedology, sedimentology, remote sensing, and mineralogy.

1. Introduction

On the occasion of the "International Workshop on Advances and Applications in Geoforensics: Unraveling Crimes with Geology", held in Messina on September 26, 2022, a wide-ranging debate among eminent participants from Europe and USA (such as Jason H. Byrd, David Canter, Lorna Dawson, Joao Fonseca, Marie-Louise Siggaard-Andersen) was launched on the role of Geosciences within the national and international forensic scenario. The contributions and topics covered in the mentioned International Workshop intended to provide a broad view of some of the most important disciplines applied in the field of Forensic Geosciences (Baldino *et al.* 2023; Byrd and Sutton 2023; Marra 2023; Marra, Di Silvestro, and Somma 2023; Morabito, Mondello, and Somma 2023; Morabito and Somma 2023; Somma 2023b; Somma *et al.* 2023a,b,c; Somma and Maniscalco 2023; Somma *et al.* 2023d; Somma, Sutton, and Byrd 2023; Tagliabue *et al.* 2023a; Tagliabue *et al.* 2023b). Generally speaking, Forensic Geosciences (or Forensic Geology or Geoforensics) may be defined as the reference discipline that applies the scientific principles and techniques of Geosciences (also known as Earth Sciences) to solve criminal cases (Murray and Tedrow 1975; Murray 2004a,b; Pye 2005; Pye 2007; Di Maggio *et al.* 2014; Donnelly *et al.* 2021) assisting law enforcement and judicial system, re-constructing events, or providing evidence then potentially used in a court of law (Saferstein 2018; Donnelly *et al.* 2021). Despite Forensic Geosciences play a marginal role in the Italian academic and scientific environments (Somma and Costa 2022), they are well established in the international scenario in both academic and non-academic circles (Donnelly *et al.* 2021). However, connecting these scientific disciplines and establishing a meaningful dialogue have proven to be difficult. There is a deeply embedded disciplinary isolation regarding journals, conferences, academic structures, policies, and commercial frameworks. What has been described above unconsciously restricts opportunities for lasting disciplinary cross-over (Donnelly *et al.* 2021). Also, Forensic Geosciences are widely used to engage students in scientific exploration so they can explore, examine, and reinforce the concepts and understand the nature of problems (Spoto *et al.* 2021; Spoto, Somma, and Crea 2021), providing, thus, innovative ways to engage even reluctant students in scientific reasoning and activity and help them to understand and comprehend real and authentic problems (Williams *et al.* 2004; Somma 2022). It is important to note that the most common fields of activity faced by forensic geoscientists may be summarized as (1) crime scene examination (Donnelly *et al.* 2021); (2) forensic soils and traces/micro-traces comparisons (Bull *et al.* 2004; Murray 2004a; Ruffell and McKinley 2008; Di Maggio and P. M. Barone 2017; Donnelly *et al.* 2021); (3) provenance and source-to-sink studies on geological and soil samples (Pirrie, Dawson, and Graham 2017); (4) soil surveying for clandestine burials (corpses, weapons, money, narcotics, fugitive bunkers; Ruffell and McKinley 2005; Ruffell *et al.* 2017; Sagripanti *et al.* 2017; Somma *et al.* 2018; Donnelly *et al.* 2021; Rocke, Ruffell, and Donnelly 2021; Ruffell and Parker 2021; Rocke and Ruffell 2022; Somma 2022; Somma and Costa 2023; (5) environmental forensics (Ruffell and Kulessa 2009; Pirrie, Ruffell, and Dawson 2013; Donnelly *et al.* 2021; Ruffell and Parker 2021). The applications of Geosciences to criminal investigation may provide useful data in the context of numerous types of offenses, both criminal and civil (Di Maggio and P. M. Barone 2017).

The present paper aims to introduce Forensic Geosciences, dealing with different areas of Geosciences such as Geochemistry, Geophysics, Remote Sensing, Sedimentology, and Mineralogy.

2. Forensic Geochemistry

Geochemistry has broad and multiple applications in Criminalistics. The application of modern and advanced analytical techniques provides important information on the characterization of solid geological materials[1] and fluids[2]. This discipline, therefore, not only allows the determination of the composition of the details of materials but also allows, through the data processing, to understand their origin and evolution. For instance, geochemical analysis, if properly applied, can be extremely useful in all those cases where it is necessary to verify and assess the environmental pollution in different matrices, such as water and soil, by contaminants and hazardous substances. These analyses make it possible to ascertain the concentration, origin, and potential interaction between different pollutants, providing factual evidence in the context of environmental surveys, waste disposal, and safety in general (Ruffell and McKinley 2008). The geochemical analyses of inorganic and organic compounds in criminalistics can determine the type of contaminants, provenance, and interaction processes between chemical contaminants and contaminated areas (Whyte *et al.* 2021). Geochemical surveys can also support investigating events such as murder,

[1] Such as soil, rocks, minerals, and gems.
[2] Such as water, hydrocarbons, and gas.

rape, and theft (Dawson *et al.* 2021). In cases of corpse concealment underground, Geochemistry of the waters may assist investigators in localizing the source area of the human decay leachate of the corpse (Donnelly *et al.* 2021). The geochemical analyses, mainly applied in criminalistics, are also aimed to analyzing elements, isotopes, and hazardous compounds (Migeon, Pili, and Bourdon 2020). The isotopic composition of geological material can provide relevant information to delineate the story of a crime. Moreover, this type of analysis makes it possible to date the material (Inkret *et al.* 2021). Especially in crimes against the environment, such as pollution or environmental disaster (Somma 2023a), the tracing of contaminated groundwaters by means of the isotopic composition characterization is crucial into reconstructing the underground circulation of pollutants. Obviously geochemical surveys related to polluted groundwaters are strictly connected with careful hydrogeological research for reconstructing the underground circulation and hydrogeological parameters. It must be underlined finally that the identification of groundwaters devoid of the specific investigated pollutant, in the areas localized higher in altitude with respect to the pollution source, is of paramount importance, for excluding possible natural contamination phenomena.

3. Forensic Geophysics and Remote Sensing

Nowadays, sophisticated and emerging crimes are at risk of being unpunished due to the lack of adequate investigation tools. In this regard, forensic investigations, especially geophysical methods, would pave the way for applying laws in the face of these crimes. In terms of criminal issues, to elaborate on a successful criminal conviction, locating physical evidence is of great importance (De Giorgi *et al.* 2020). For instance, geophysical methods are used to identify items, buried in the underground and due to illegal concealments, including drugs (Cadwell 2020), landmines (Madzunya *et al.* 2021), improvised explosive devices (Baldaino *et al.* 2021), and explosives (Shvedchikova, Moghaddam, and P. Barone 2021), toxic and hazardous wastes (Franceschetti *et al.* 2021) in illegal dumps (Kootker *et al.* 2020; Davis, Whitehead, and Lengke 2022), weapons and weapons caches (Cadwell 2020; Harvey and Sekulla 2021), and corpses in clandestine graves (Somma and Costa 2022; Byrd and Sutton 2023; Somma, Sutton, and Byrd 2023) or mass genocide graves (Ekštajn, Kružić, and Basic 2021).

Variable forensic techniques are currently used and all are aimed to perceive one crucial goal, recognizing anomalies in the physical parameters investigated. Among the most widespread geophysical techniques used in earth sciences issues, there is a plethora of active and passive methods (seismic, gravimetric, electrical, magnetic, electromagnetic, radiometric; Ruffell and McKinley 2008). In many countries, a search strategy is, by obligation, involved in any case since the early stage of investigation for deciding the most appropriated approach and method to apply in order to gain the highest probability of search success (Ruffell and McKinley 2008; Donnelly *et al.* 2021). Investigations for near- and far-field search activities start from the large-scale remote sensing methods (Pensieri, Garau, and P. M. Barone 2020), surface geomorphology changes (de Bruin and Schmitz 2021), aerial (Rocke, Ruffell, and Donnelly 2021) and ultraviolet photography (De Angelis *et al.* 2020), to ground-based observations of vegetation changes (Finkelstein, Rosengarten, and Levy 2020), thermal imaging (Listos *et al.* 2021), soil type and depositional environment (Xu *et al.* 2020), near-surface geophysics (Weiss and Roy 2020), diggability surveys (Somma *et al.* 2018; Lockwood and Masters 2021) and probing of anomalous areas before topsoil removal and finally controlled stratigraphic and archaeological excavation and recovery (Marra 2023).

Near-surface geophysical methods are based on the contrast detection between the target signal and the host materials' noise. Although using Ground Penetrating Radar (GPR) (Amran *et al.* 2020) may be the dominant geophysical method, recent studies suggested as more appropriated the use of multi-method approaches (Osbourne and Christensen 2020). For instance, electro-magnetic (Mankoff *et al.* 2020) and electrical resistivity surveys are relatively fast in the data acquisition during the investigation of anomalous areas and provide high resolution results. Concerning the limitations of the GPR method, other studies showed that the GPR is not relevant in specific search environments, including clayey material (Canata *et al.* 2020) and heterogeneous soil types (Dong *et al.* 2020), which are significantly attenuating radar signal amplitudes. Also, the GPR method showed its limitation in water-logged, saline-rich, wooded environments, and depth of investigation. Magnetic methods are passive and measure slight changes in the Earth's magnetic field and its derivative (magnetic susceptibility) due to nearby objects. When a magnetic field is applied to soil and rock, the degree of magnetization can be measured as the magnetic susceptibility. The complexity of the matter lies in the combination of mineralogical dia-, para- and ferro/ferri-magnetism and geochemical magnetization related to trace elements. Previous studies (Pringle *et al.* 2015) argued that the magnetic approach is not always the best tool for forensic investigation and control search studies, due to the possibility of bias due to interference. Nonetheless, according to Leucci (2020), magnetic surveys are quite relevant after removing artifacts created during data collection. There are wide variations in measured magnetic susceptibility reported between different rock and soil types, with the most significant values partly attributable to the relative proportions of magnetic minerals in the material. In soils, the ferrimagnetic mineral maghemite[3] has a dominant effect on magnetic susceptibility. Therefore, the magnetic susceptibility has been used for site soil characterization, forensic trace evidence, and environmental forensic pollution studies (de Caritat *et al.* 2021), namely during the polluted era of the Anthropocene (Essefi 2021). In urban depositional environments, magnetic methods have poorly provided positive results in search for simulated clandestine graves. In contrast, magnetic surveys, commonly used in archaeological searches (Mahaney 2020), have successfully located areas of historic surface burning as the weakly magnetic iron oxide minerals of the soil are transformed into the highly magnetic minerals magnetite and maghemite.

Environmental crimes may be recorded by the pedological covers. In a forensic investigation, demonstrating the relation between variations in the soil properties and dissimilarity between questioned and control samples is an important issue. Magnetic parameters are important in characterizing materials, and detectable quantities of magnetic minerals are almost always found in soils. In forensic investigations, it is important not only to obtain representative and comparable analytical data but also to develop standardized protocols and frameworks of best practice for better evaluating soil properties. Several experiments

[3]A low-temperature, oxidation weathering product of the strongly magnetic minerals magnetite and titanomagnetite.

on the magnetic susceptibility of soils have been conducted recently, primarily related to pollution monitoring and mapping.

Remote sensing methods are aimed at obtaining information on the ground surface and subsurface, included specific targets present therein, without a direct contact with the territory by examiners (Ruffell and McKinley 2008). In inaccessible or dangerous places remote sensing expands the supervision of law enforcements and forensic experts. It may make up for the lack of workforce and reduce the exposure of these agents to dangerous circumstances on the ground. In a such complex context, remote sensing activities involving the field of image intelligence may allow to individuate specific targets by means of analysis of imagery obtained using electromagnetic devices (based on X-rays, ultraviolet, visible, LiDAR[4], infrared, radio microwave energy) mounted on satellite, airplan, and UAV[5] for the surveys of the ground (Ruffell and McKinley 2008).

Forensic activities based on remote sensing may involve environmental crimes, crimes against animals and wildlife, mining frauds, and the search for missing people. One of the new frontiers of forensic remote sensing is to face transnational organized crimes and terrorism (Avtar *et al.* 2021; Puttonen and Romiti 2022).

4. Soil Forensics, Forensic Sedimentology, and Forensic Mineralogy

Soil forensics, that in certain circumstances may also correspond to Forensic Sedimentology, studies and analyzes soils connected to a crime (Xu *et al.* 2020). In forensic analysis, soil has a double meaning, referring both to any material of geological origin that consists of unconsolidated constituents, such as a sandy beach and mud sediments or to soils *s.s.* (Profumo *et al.* 2020). The sediments/soils can provide important information to link the actor of a crime (victim or suspect) to a place and clarify the dynamics of the events and the reconstruction of historical facts. This liaison depends on the possibility that these geological materials can be transferred (Locard principle) from one place to another site or items for filing on moving surfaces, such as shoes, tires, or work tools. Many crimes are committed outdoor, where the environment can exchange its organic and inorganic materials with actors of crimes. Due to the complexity of soils, there is a noticeable variability between soil samples, recording significant variations in the texture, structure, composition, and proportions, even in small areas and spaces, both in the horizontal and vertical dimensions along the pedological profile (Tagliabue *et al.* 2023b). The precise analysis of the terrain allows a characterization of the samples to the point that it can be distinguished whether they were collected a few meters away each other. For this evidence, geological and pedological soil analysis is excellent for forensic investigations (Di Maggio and P. M. Barone 2017). Despite recent criticisms (Douglas, Graan, and Hardenstine 2020; Melo *et al.* 2020), Forensic Sedimentology and Soil Forensics, also thanks to the contribute of micromorphology, may provide very successful results into establishing connections between people, objects, and places. With the development of modern analytical technologies, both have become leader disciplines in Criminalistics (Somma 2023c).

Experts in Forensic Sedimentology, in particular, examine the surface, texture, and composition of the inorganic grains via binocular, optical microscope, and scanning electron

[4]Laser imaging Detection And Ranging.
[5]Unmanned Aerial Vehicle.

microscope. Grains may be analyzed individually or in thin sections of aggregates included in epoxydic resins. Methods devoted to the color analysis are commonly used in the finest fractions of the samples (Somma *et al.* 2023d).

Cases usually managed by sedimentologists and soil scientists may involve a wide range of crimes occurred outdoor in the countryside, such as environmental violations, murder, theft, or kidnapping, and prevention of war victims (Inkret *et al.* 2021).

Mineralogical investigations often involve the collection of geological and soil traces and micro-traces from a questioned item, such as boots, vehicles, tools, or corpses (unknown samples), followed by sampling of soils and sediments from the crime scene or *alibi* sites (known samples). These activities are accompanied by the description, characterization, and the application of appropriate analyses with comparative purposes. Integration and extrapolation of this information can then be scaled up to build a coherent model of sample information – from the initial trace observations, trace collection, and trace specimens reported on maps of the surface of the investigated items (such as a sole of a footwear) to the landscape scale, with the realization of GIS[6]-based soil/geological/land cover maps, accompanied by appropriate evaluation of the ensuing results. Established concepts and standardized approaches in Geology and Mineralogy are vitally crucial in applying Geology within the criminal justice systems worldwide. Our global safety and security depend upon sharing best practices and collaboration. Such quality best practice approaches can also be applied to Forensic Mineralogy in wildlife, art, ballistics and drug crime (Ruffell and McKinley 2008; Di Maggio *et al.* 2014; Di Maggio and P. M. Barone 2017) and gemstone frauds (Spoto 2023).

The advantages and disadvantages of a range of mineralogical methods can be adopted and recommended. Type of sample, size, and type of analytical method, whether the method is destructive or non-destructive, sampling procedures, analytical conditions, and accreditation shall consider the best practices. The common analytical approaches using optical microscopy, scanning electron microscopy, X-ray diffraction, infrared spectroscopy, Raman spectroscopy, X-ray fluorescence, thermal analysis, and much more can be used to this end in forensic contexts (Murray 2004a,b; Ruffell and McKinley 2008; Di Maggio and P. M. Barone 2017; Donnelly *et al.* 2021). In recent times, a careful description of the most accredited best procedures and methods to adopt in geological and soil evidence investigations is reported in the BPA[7] (Bourguignon *et al.* 2019) prepared by the APST[8] of the ENFSI[9].

5. Conclusions

Significant advances in the Forensic Geosciences have occurred over the last decades with a successfully application of Forensic Geochemistry, Geophysics, Sedimentology, Geopedology, Remote Sensing, and Mineralogy in criminalistic issues.

[6]Geographical Information Systems.
[7]Best Practice Manual.
[8]Animal, Plant and Soil Traces expert working group.
[9]European Network of Forensic Science Institutes.

Traditional serious crimes may damage a person or a small group, while environmental crimes threaten humanity. The application of Forensic Geosciences methods has strengthened the interpretation of environmentally polluting activities as crimes against the environmental heritage, intensifying, thus, the law enforcement efforts in contrasting illegal activities. Further, setting standards to limit and know criminal activities represent urgency. Creating shared investigation protocols involving forensic geosciences techniques should be of absolute priority in the Italian law enforce criminalistic units. Minimizing time and cost factors and maximizing the amount of data, information, and knowledge available should be the new challenges to be faced in short and medium-term strategies.

Author contributions

Conceptualization, S.E.S.; methodology, S.E.S., R.S.; software, S.E.S., R.S.; validation, S.E.S., R.S.; formal analysis, S.E.S., R.S.; investigation, S.E.S., R.S.; resources, S.B., S.E.S., R.S.; data curation, S.E.S., R.S.; writing original draft preparation, S.E.S.; writing review and editing, R.S.; visualization, S.E.S., R.S.; supervision, R.S. 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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[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] Università degli Studi di Catania,
Dipartimento di Scienze Biologiche, Geologiche e Ambientali,
Corso Italia 57, 95129 Catania, Italy

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

* To whom correspondence should be addressed | email: sebastiano.ettore@gmail.com

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