

## MEASURING COLOR TECHNIQUES FOR FORENSIC COMPARATIVE ANALYSES OF GEOLOGICAL EVIDENCE

ROBERTA SOMMA <sup>ab</sup>, SEBASTIANO ETTORE SPOTO <sup>a\*</sup>,  
MARCELLO RAFFAELE <sup>c</sup> AND FABIO SALMERI <sup>c</sup>

**ABSTRACT.** In Forensic Geology, color examination of sediments and soils is one of the first analyses for exclusionary/comparative purposes. Forensic colorimetry deals with the examination of the color of physical evidence related to criminal investigations. Color of soils and sediments has always been considered an essential parameter and one of the most common and crucial visually physical property for characterizing, describing, and comparing these geological materials, since the first steps of forensic investigations. This parameter may be evaluated both qualitatively and quantitative. In forensic comparative analyses of sediments and soils, most of the colorimetric methods are nowadays computational. These computational instruments, provided of standards and standardized illumination conditions, may obtain very high-resolution and non-destructive quantitative data. When adapted to sedimentological applications for forensic purposes, photometric instrumentations are powerful tools due to their low purchase and maintenance costs. Moreover, some devices are also portable and easily used at the crime scene. Recent advances in the colorimetry research showed as also the simple use of digital devices, such as low-cost flatbed scanners, may be easily applied for the color examination of acquired color images of sediments and soils, if calibrated with standards, as reference charts or database. The results of a simulated forensic casework devoted to the comparative analysis of the color of soils, acquired by means low-cost flatbed scanner, confirmed previous results on this useful application.

### 1. Introduction

Colorimetry is widely applied in many scientific fields (Bornemann and Dörsam 2013). The examination and description of the color shown by certain geological or anthropogenic materials, such as sediments, soils, pigments, or dyes are a goal of several disciplines/fields, such as geology (Murray 2004a; Pye 2007), soil sciences, chemistry (Reeder *et al.* 2014; Wright *et al.* 2015; Choi *et al.* 2018; Blanco *et al.* 2020; Puleio *et al.* 2020), industry, engineering issues (G. M. Brown 2000; Cucinotta, Raffaele, and Salmeri 2019, 2020; González-Merino *et al.* 2021; Barberi *et al.* 2022; Lo Giudice *et al.* 2022; Baldino *et al.* 2023; Somma *et al.* 2023a,b) and archaeology (Ferguson 2014; Ruck and C. T. Brown 2015). Forensic colorimetry (also known as forensic color analysis) deals with the examination of the color of physical evidence related to criminal investigations. Color of soils and

sediments has always been considered an essential parameter and one of the most common and crucial visual physical property (Ciolkosz and Luxmoore 1993) for characterizing, describing, and comparing these geological materials, since the first steps of forensic investigation (Murray 2004a). Forensic geologists and soil scientists usually examine color of geological evidence (soils and sediments) collected at crime scene or on items of investigative interest, being the color examination an accepted method (Murray 2004a; Di Maggio *et al.* 2013; Bourguignon *et al.* 2019; Donnelly *et al.* 2021), useful for an overall forensic examination for exclusionary/comparative purposes (Donnelly *et al.* 2021). Colors may allow to distinguish mineralogical composition and sedimentary facies between marine and continental sediments and may be helpful for interpreting variations in sea level, oceanic circulation, sedimentation rate, and primary productivity (Myrow and Landing 1992; Leszczynski 1993). The color of sediments and soils may vary from yellow to brown or red; shades of grey, white, black, green, and blue are also common (Pye 2007). The apparent color of soils depends on the structural and optical properties of the mineral grains (refractive index, crystalline structure, density, ionic composition, texture of the surface), grain staining or coatings, organic matter content, water content, ion concentration, as well as on the illumination conditions under which the material is observed (Pye 2007). The colors of sediments can have complex origins and, in some cases, have a secondary origin. However, colors reflect also important aspects of depositional environments, including redox conditions and rates of deposition of organic matter. Colors are generally controlled by accessory minerals and compounds of iron and organic carbon (Pettijohn 1975; Potter, Maynard, and Pryor 1980; Myrow 1990). Compounds of other transition metals (e.g., Ti, Mn, Co, Cu, and Zn) also occasionally may impart peculiar colors.

On the base of the above, considered the complexity of the color origin, it is evident that the colorimetry of soils and sediments may be a very complex task, whatever is the analytical method used. This research is devoted to a short review on the color of geological materials, the sample preparation, and the main methods used in forensic geology for the comparative investigations of the color of geological evidence. The results related to a simple simulated casework concerning the color examination and comparisons of forensic soils and sediments are also reported and discussed.

## 2. The color of sediments and soils

Soils are characterised by an extremely heterogenous nature (Sumner 1999). The colors of sediments and soils fall mainly within two *spectra*: i) green-gray to red and ii) olive-gray to black. The green-gray to red color *spectrum* is mostly controlled by the oxidation state of iron, specifically the  $Fe^{3+}/Fe^{2+}$  ratio in various minerals, and not by the total iron content (Tomlinson 1916; McBride 1974). In particular, the color is a function of the mole fraction representing the proportion of iron in the  $2+$  state ( $Fe^{2+}/Fe^{2++} + Fe^{3+}$ ) per gram of rock. In relatively unoxidized *strata*, green colors result from the presence of iron-bearing phyllosilicates such as chlorite, illite, and in some cases, glauconite. Kaolinite and smectite provide white to light neutral colors. The red coloration is due to clay-iron oxide coatings on the surfaces of the grains (Folk 1976; Pye 2007), whereas less common yellows and browns generally result from limonite and goethite. Red hematitic staining is typically an early diagenetic *phenomenon* resulting from: (1) dehydration reactions in

which limonite stains on detrital particles are altered to hematite; (2) dissolution of iron silicates and precipitation of the released iron; and (3) direct oxidation of magnetite and ilmenite grains (Hubert and Reed 1978). Very low levels of hematite can impart a deep red coloration. The conversion from red to green colors occurs by the reduction of the iron, which is either carried away in solution or reprecipitated as iron-rich clay minerals such as chlorite (Thompson 1970). The strength of red or green color is a function of grain size, with fine-grained rocks having higher iron content and thus more intense color. This relationship is due to *amorphous* or poorly crystalline iron oxides (McPherson 1980). Changes in the oxidation state of iron, and hence of the color, result from interactions with altering fluids at any time in the post depositional history of a unit and are thus controlled in part by permeability. Oxidation or reduction spots are due to incomplete diagenetic alteration of a layer. The olive-gray to black color *spectrum* is a function of Total Organic Carbon (TOC), with darkest colors corresponding to highest carbon contents. This relationship is empirically confirmed in studies of modern sediment (Sheu and Presley 1986). The main controls on organic carbon contents include the accumulation rate of organic matter, sediment accumulation rate, organic compound decay rate, and oxygen levels (Potter, Maynard, and Pryor 1980). Thermal maturity may also be an important factor in influencing the color. For instance, (Lyons 1988) demonstrated that the black color of some deposits is due to the carbonization of very small quantities of organic matter (0.06 percent TOC). Diagenetic loss of carbon leads to lighter colors. The carbon *reservoir* shields the iron-bearing minerals from oxidation until most of the carbon is oxidized, producing in the sediment green-to-red color *spectra*. Oxidative loss of carbon and red coloration occur when bottom waters and/or pore-fluids are highly oxygenated. Green colors result from sediment deposition with low organic content and weakly reducing to oxidizing conditions. Gray to black colors are also associated with environments showing dysaerobic to anaerobic bottom waters and may depend on the presence of disseminated pyrite. During burial diagenesis, metastable minerals such as mackinawite (FeS) and greigite ( $\text{Fe}^{2+}\text{Fe}^{3+}_2\text{S}_4$ ) may be transformed into submicron-sized framboids of pyrite (Raiswell and Berner 1986). Mn oxides or Fe-Mn oxides such as pyrolusite may also impart dark colors. Sediments with siderite appear gray to bluish (Pettijohn 1975).

### 3. Materials and methods

Forensic Geology is the application of principles and methods of earth sciences for the solution of criminal cases (Tindall 1994; Murray 2004a,b; Ruffell and McKinley 2008; Di Maggio *et al.* 2013; Donnelly *et al.* 2021; Somma 2022). Forensic activities carried out by forensic geologists may concern cases of corpse concealments (Marra 2023), environmental crimes (Morgan and Bull 2006; Spoto, Somma, and Crea 2021), conflict minerals (Donnelly *et al.* 2021; Spoto 2023), fossil fakes (Marra, Di Silvestro, and Somma 2023), and comparative analyses and provenance studies of geological evidence (Pirrie, Dawson, and Graham 2017). In such forensic activities, color examination of minerals, sediments, and soils is one of the first analyses to accomplish (Murray 2004a; Pye 2007; Ruffell and McKinley 2008; Di Maggio *et al.* 2013; Donnelly *et al.* 2021; Somma 2023a,c; Spoto, Barone, and Somma 2023). This examination may be based on subjective qualitative descriptions or objective quantitative methods. In the latter cases,

instruments are able to provide a color determination in numerical terms of color space and notation system, and are based on the use of standards, standardised conditions of illumination, and data recording (Murray 2004a; Pye 2007). Whatever is the approach used, the most common color notation systems for quantifying the color value are expressed with XYZ *tri-stimulus* values (*Commission Internationale de l'Eclairage* 1931), L\*a\*b\* parameters (*Commission Internationale de l'Eclairage* 1978; Munsell Color 1994), and Munsell system HVC attributes. The *tri-stimulus* XYZ system is based on attributes related to three color *stimuli* detected by the human eyes. The RGB color notation system represents color using three basic color components: red (R), green (G), and blue (B). Each component can take a value from 0 to 255, being the *minimum* and *maximum* intensity of the component, respectively (Yang *et al.* 2022). The L\*a\*b\* system (Azetsu and Suetake 2021) derives from *tri-stimulus* XYZ system, being a mathematical derivative (Pye 2007). The L\*a\*b\* parameters are conceptualized in terms of a spherical color space, corresponding to brightness, redness-greenness, and yellowness-blueness, respectively (Pye 2007). The Munsell HVC parameters (Kurniastuti *et al.* 2022) correspond to Hue, Value, and *Chroma*, respectively. Hue refers to the color itself (red, yellow, green, blue, purple color). Value refers to the lightness or darkness of the color (lightness), *i.e.* the amount of light reflected by the sample. *Chroma* represents the purity or vibrancy of the color (saturation). Finally, color may be also expressed in terms of percentage reflectance values at different wavelengths (Pye 2007).

**3.1. Treatments of the geological evidence.** The color of soils, sediments, and coherent rocks exposed on the outcrops can significantly change over distances of only a few centimetres, both on the ground and in depth (along the stratigraphic layering or geopedological profile), as well as with the time due to seasonal and environmental fluctuations (Pye 2007). Analogous color variations may also occur in laboratory after the sampling activities, if the storage conditions of the geological samples are very different from those of the original site of collection (Pye 2007). Different modifications of the color, due to the evolving oxidative state of the minerals, may occur when color examination is made in different times and without assuring a standard in the preservation and storage conditions of the samples (Pye 2007). Forensic color descriptions and comparisons are usually done in laboratory on air dried disaggregated bulk samples (Pye 2007). Treatments of the forensic geological samples are crucial for eliminating substances influencing the color, such as water/moisture, organic matter, and iron oxides (Sugita and Marumo 1996; Di Maggio *et al.* 2013). After these treatments, color determination may allow to distinguish up to 97% of specimens (Sugita and Marumo 1996). It is of paramount importance that, whatever treatment is done, both compared samples need to be treated in the same way (Donnelly *et al.* 2021). Additional results may also be obtained in samples after oven heating or ashing, after organic matter decomposition, and after iron oxide removal (Sugita and Marumo 1996), as well as in moist samples, and different particle size fractions, obtained by means of wet or dry physical sieving, before and after crushing or milling in an homogenous finest grain size matrix (Sugita and Marumo 1996; Croft and Pye 2004; Murray 2004a; Pye 2007; Donnelly *et al.* 2021). The color analysis on the clay fraction of the sediments and soils (< 4 µm) is also suggested (Di Maggio *et al.* 2013) because usually pigments are particularly concentrated in the finest grain deposits. Croft and Pye (2004) proposed to examine the color on the fraction

< 150  $\mu\text{m}$ , after oven drying at 40°C for 4 hours, and before and after grinding to finest grain sizes. Other experts proposed to determine the color on the fraction < 2 mm, after oven drying at 100°C (Murray 2004a) or 110°C for 4 hours, successively ashed at 850°C for 30 minutes (Dudley and Smalldon 1978). Analyses on sub-samples of bulk sample may be also very useful (Pye 2007). These different procedures may also help to individuate the main factors influencing the color (Pye 2007).

**3.2. Munsell soil-color charts.** Color examinations are commonly based on comparisons of the geological sample with reference charts. The most widespread and traditional qualitative method in forensic geology (Sugita and Marumo 1996; Di Maggio *et al.* 2013; Donnelly *et al.* 2021) is based on visual comparisons of the color of the investigated soil sample with the color reported in reference charts, contained in the Munsell handbook (Munsell Color 1994; Sugita and Marumo 1996; Murray 2004a; Pye 2007; Cochrane 2014; Awais 2023). In the case of rocks, the visual comparison of the color is based on the use of the Geological Society of America Rock Color Chart (Goddard *et al.* 1948). The examination of the color by visual comparison allows to evaluate the approximate Hue (or color), Value (or lightness), and *Chroma* (or saturation) of soils/sediments by comparing the samples with the handbook containing the standard Munsell color charts. In such method, it is necessary to compare the color of the material investigated with the color reported in standard color chips, divided into discrete elements (Baek *et al.* 2023). A uniform illumination and a neutral background, in order to limit the environmental influences on the perception of color, are required (Jiang *et al.* 2021; Baek *et al.* 2023). Visual comparisons may be done in the field or in laboratory. The best practise for visual comparison with Munsell charts in laboratory consists of using natural light, near a window exposed to the North (Murray 2004a) at 12 of clock. The method presents certain limitations, due to the different perception of color depending on variable lighting conditions, personal skill and experience of the observer, and other subjective factors. In other words, the color being described by means of chart-based comparative methods, is unavoidably subjective (Pye 2007).

**3.3. Flatbed scanners.** In recent times, the use of digital photography of soils and sediments, acquired through scanner systems (such as flat-bed scanner) or telecameras (Vil-lafuerte and Negro 1998; Kemp 2014; Kirillova, Kemp, and Artemyeva 2017; Oliveira, Zocchi, and Jacomino 2017), associated with a data post-processing phase, is a new growing application able to provide a color description in numerical terms of color space and notation system. The method for color examination of digital photography of geological sample, acquired by low-cost flatbed scanners, measures the amount of light reflected from the questioned surface at high-resolution. The image processing, using color analysis software, is aimed at extracting the color data, eliminating noise, and correcting illumination. The software may use different color notation systems among  $L^*a^*b^*$ , Munsell system HVC, and RGB (Yao 2011). Converting color data into different notation systems can provide useful information on color properties and allow comparisons. It is, therefore, necessary to ensure that the image acquisition is performed with image acquisition devices calibrated for obtaining accurate and reproducible color measurements. The main advantage of this method is represented by the possibility of imagining a large sample surface area, ensuring greater color representativeness. Furthermore, the technique allows the color to be assessed

objectively, avoiding the variability of the human observer. However, the method may have limitations related to the nature of the sample, illumination (Baek *et al.* 2023), the precision of image processing, and the choice of color model used for color description (Sarkar *et al.* 2021). According to this approach, the possibility to convert the RGB values of the images into the Munsell color space is relevant allowing to determine the color by simply acquiring a photograph. Several applications and digital tools may use the Munsell tables for automating color measurements and selection. Color management software allows to select colors, based on Munsell tables, and display them in real-time on a screen. These capture devices use Munsell tables as a reference for measuring HVC (Kirillova *et al.* 2018; Milotta *et al.* 2018; Mancini *et al.* 2020; Milotta *et al.* 2020). Research on feedforward networks and the convolutional neural networks accomplished for predicting the HVC of the Munsell soil-color charts from RGB data captured by photographs is a recent frontier (Solis, Munoz-Alvarado, and Pegalajar 2022). The convolutional neural networks revealed to be the best model obtaining percentage equal to 93% for the accuracy of HVC measurement related to 2856 images of the Munsell charts. These promising results led to consider the model as an available candidate for testing the convolutional neural networks on real images of soils and sediments for the color determination (Solis, Munoz-Alvarado, and Pegalajar 2022).

**3.4. Spectrophotometers.** Color measurements of substances may be realized by means of photometric devices, whose functioning is based on the Lambert Beer Law. The color densitometers are usually applied for measuring the density of primary colors. These may be also used in chemical analyses for measuring the concentration of a colored solution or the amount of a solute in a mixture of substances in a colored solution, and determining the differences in color of mixtures of substances. The color photometers are colorimeters using monochromatic LED RGB light sources, for illuminating the substance. This technique, valid only for monochromatic light, states that the concentration of a solute in a homogeneous solution is directly proportional to the absorbance of the solution. Spectrophotometers are instruments that allow the measurement of the absorption or transmission of light by samples, after having been irradiated with light of suitable wavelengths, which can cover the wavelength range of the ultraviolet and visible *spectrum*. Recent advances in this technology are represented by handheld spectrophotometers able to match sample color with database colors without other devices. Spectrophotometric color determinations of soil and sediment are usually carried out in forensic geology applications (Croft and Pye 2004; Pye 2007; De Carvalho *et al.* 2013; Di Maggio *et al.* 2013; Neuhauser and Handler 2013; Pozo-Antonio *et al.* 2017; Singh *et al.* 2017; Avendaño Arenas, Astorga Gallardo, and Cabezas Osorio 2021). The spectrophotometer devices differ from the color photometers, being able to measure the absorbed or transmitted light at different wavelengths, usually in the visible *spectra* between 400 nm and 700 nm. Different types of spectrophotometers, from small handheld devices to large benchtop instruments, are used depending on the desired functionality and necessity (devices with 0°/45° configuration, spherical spectrophotometers, multi-angle spectrophotometers, diffuse reflectance spectrophotometers (Torrent and Barrón 1993). Measurements may be expressed in different color notation systems among L\*a\*b\*, Munsell system HVC, and spectral percentage reflectance values at different wavelengths (Pye 2007).

#### 4. Simulated forensic casework

A serious crime was simulated in 2019 outdoors in the Peloritani Mountains' hills during the rainy season, near to the city centre of Messina (Italy). A dressed body was found supine outdoor, on the ground, with evidence of injuries by firearms. No traces of firearm, bullets, and blood were present on the scene. Two suspects to be the authors of the crime and their dirty shoes were seized the same day of the victim finding.

**4.1. Forensic colorimetry.** Comparative examinations of eighteen specimens of geological evidence collected at the crime scene, and on the suspects' and victim's shoes and clothing were accomplished for ascertaining the provenance. In particular, abundant traces of sediments were collected inside the pockets present in the back side of the victim's trousers and on the footwear soles of suspects 1 and 2. The size of geological evidence related to the unknown samples was relevant (around 5 g), due to the suitable weather conditions (wet soils because of rains). The treatment of the specimens consisted in oven drying, organic matter decomposition, and iron oxide removal according to protocols reported in Sugita and Marumo (1996). The specimens were dry-sieved and the color was determined on the finest inorganic fractions.

The tools used for the color examinations were: i) the Munsell soil-color charts; ii) a low-cost commercial flatbed scanner (model Epson perfection 640U with resolution from 600x600 to 9600x9600 dpi, scan velocity 16 msec/color line, color depth 36 bit) provided of commercial software for image acquisition and post-processing. The results of the color evaluation by visual comparing the Munsell soil-color charts were reported in Table 1. Geological evidence from victim, suspect 1, and suspect 2 resulted to be characterised by the same color light olive brown (2.5Y 5/3, Table 1). Differently, the color resulted light olive gray (5Y 6/2, Table 1) in the samples related to the crime scene.

The two charts related to the identified Munsell colors and geological evidence were placed in transparent minigrip envelopes and scanned by means flatbed scanner. Ten points of measures were acquired for each sample at 300 dpi and colors expressed in mean values of RGB coordinates for each image (Table 1). The average measurements were calculated and reported in the histograms of Figure 1.

TABLE 1. The color of the samples was determined by means of the use of the soil-color charts of Munsell.

<b>Geological evidence</b>	<b>Munsell color (Hue Value/Chroma)</b>	<b>RGB mean values corresponding to Munsell color</b>
Crime scene	5Y 6/2	159,146,128
Victim	2.5Y 5/3	144,119,116
Suspect 1	2.5Y 5/3	144,119,116
Suspect 2	2.5Y 5/3	144,119,116

The results of the color measuring on RGB images acquired by flatbed scanner were reported in Figures 1 and 2. Comparing all the sample colors, it was possible to observe as the RGB color of the victim's sample was similar and overlapped to the RGB color of

suspect 1's sample. Differently, the colors related to the victim's, suspect 2's, and crime scene samples were clearly differentiated (Figures 1, 2).

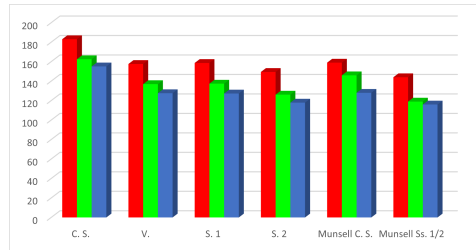


FIGURE 1. Mean values of the RGB colors of the samples. Measures were acquired by means of flatbed scanner in 18 samples. Each measure was related to ten points for each specimen for a total of 180 measures. RGB values related to the Munsell charts corresponding to the samples (Table 1) were also reported as standard. Acronyms: C. S. = Crime Scene; V.=Victim; S. 1= Suspect 1; S. 2= Suspect 2.

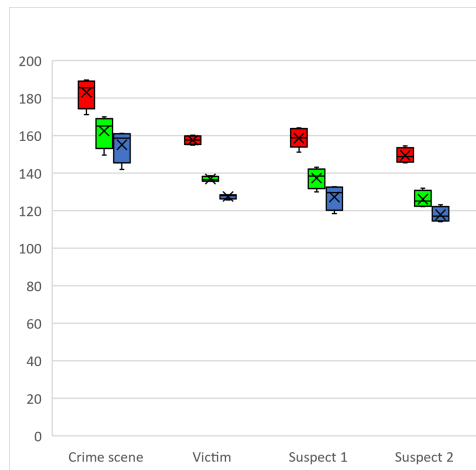


FIGURE 2. Box plots of the RGB colors related to geological evidence collected at crime scene, on the victim trousers and suspects shoes. A significant compatibility of the victim sample's RGB colors with the suspect 1 sample's RGB colors may be ascertained, being evident the overlap between RGB data.

## 5. Discussion and conclusions

Whatever qualitative or quantitative method, device, and tool are used for the forensic color examination of sediments and soils, the same accurate treatments of the samples to compare are required. In forensic comparative analyses of sediments and soils, most of the colorimetric methods are nowadays computational. Among the different instruments used, photometric devices allow low-cost, rapid, reliable, reproducible, and accurate measures. Recent advances in the colorimetry research showed as also a low-cost digital device, such as a flatbed scanner, may be easily used for the color examination of acquired color images of sediments and soils, if calibrated with standards, as reference charts or database. The simulated forensic casework, related to comparative analyses of the color accomplished in soil and sediment specimens, allowed to establish as the color examination of color images of sediments and soils acquired by means low-cost flatbed scanners, compared with reference charts and database, was very performant and able to better distinguish colors attributed to the same color chips of the Munsell charts. As a matter of facts, the RGB color values related to the victim's sample resulted significantly comparable with those measured in the suspect 1's sample and differentiated from suspect 2's and crime scene samples (Figure 2). Differently from the qualitative Munsell approach, where an undifferentiated Munsell chip 2.5Y 5/3 was assigned to both victim's and suspect 1' samples, the use of the flatbed scanner allowed to better differentiate the color (Figure 2). In conclusion, the comparative analyses of the color determined by means color images acquired by flatbed scanner revealed more effective than those carried out by using simply the Munsell charts. Notwithstanding, the use of the Munsell color charts still today for most experts remains a prevalent tool for the color examination, considered the easiness and rapidity in the use of these portable charts. Finally, it must be underlined that the evidential significance of the color comparison in rare cases may be considered high in a court, if considered alone. The colors of two samples, also if they match, do not represent sufficient evidence for linking a suspect to a crime, if only these results are evaluated. The characteristics of the geological evidence or of anthropogenic materials such as paints or glass, in forensic sciences are classified as class characteristics, *i.e.* features referable to a group or class of materials (Picozzi and Intini 2009; Saferstein 2017). In forensic geology it is noteworthy that comparative analyses of questioned and control samples must be based on a multi-proxy approach where several characteristics of the specimens have to be carefully investigated, compared, and contextualized in the time and space especially at outdoor crime scenes (Somma *et al.* 2018; Somma and Costa 2022; Baldino *et al.* 2023; Somma 2023b; Somma *et al.* 2023a,b; Somma and Costa 2023). The results of comparative analyses on soils may be considered provided of an elevated degree of certitude when several properties are compared. 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. In soil analyses, being complex systems, both inorganic (minerals) and organic (vegetal and animal) components have to be examined (Somma *et al.* 2023c). The color is only one of the main characteristics to analyse in the inorganic component of a soil for forensic purposes. Information provided by color, together other aspects such as the mineralogical and chemical composition, texture and grain size, luster, shape, roundness of particles, fossils, and the occurrence of peculiar grains (Somma and Maniscalco 2023) may allow to establish if a common origin may be presumed

for the compared samples. For an exhaustive investigation based on soil comparisons, also the organic component has to be analysed by forensic botanists (Morabito, Mondello, and Somma 2023; Morabito and Somma 2023) and entomologists (Byrd and Sutton 2023; Somma, Sutton, and Byrd 2023; Tagliabue *et al.* 2023). If all these chemical, physical, and biological characteristics match, the evidential significance of the geological sample may be considered high or strong. In any case, when the colors of two geological samples do not match, color determination may prove that a common provenance of sediments and soils (unknown and known samples) from a same location may be excluded (Donnelly *et al.* 2021).

### Author Contributions

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

### Competing interests

The authors declare no competing interests.

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<sup>a</sup> 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

<sup>b</sup> Accademia Peloritana dei Pericolanti,  
Palazzo Università,  
Piazza Pugliatti 1, 98122 Messina, Italy

<sup>c</sup> Università degli Studi di Messina,  
Dipartimento di Ingegneria,  
C.da di Dio, 98166 Messina, Italy

\* To whom correspondence should be addressed | email: [sebastianioettore@gmail.com](mailto:sebastianioettore@gmail.com)

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