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Soil Fingerprinting Using Structural Deformation Features

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Abstract: Fingerprinting of soil based on structural deformation features is a revolutionary step towards achieving a better geographical matching of geoscience within criminal cases, and current process is more accurate and reliable. Traditional soil analysis based on compositional data usually suffers the problem of spatial variability and environmental change due to the fact that it is not able to effectively discriminate. In this review, it is discussed that prompted by these limitations, structural geology has evolved through identification of distinctive microstructural and macrostructural features as long-lasting fingerprints of particular geological conditions, including fault gouge, breccia, foliation, lineation, and strain markers. They are made up of tectonic stresses, compactional, or shear stresses which preserve the history of deformation of soils and therefore they are suitable in forensic comparison as they cannot be altered by surface contamination or the weather. This approach combines available literature on structural soil studies, with an ocular focus toward thin-section petrography, microscopic analysis of cataclastic literature, and the macroscopic bias toward shear zones and fabric components. Integration of quantitative assays such as image analysis, X-ray diffraction are also emphasized as providing added reproducibility and objective capacity. The practical examples of these approaches in homicide investigation, trafficking activities and even environmental crimes are presented as the case studies when structural characteristics played the most important roles in connecting suspects with the place of their burial, illegitimate goods with their place of relegation, and illegal dumping of goods. The most important results support the idea of structural analysis being superior to the traditional ones when it comes to the differentiation of soils with similar composition but different geological history. The review has also pointed out several limitations of utmost importance: the potential risk of contamination, heterogeneous soil compositions, lack of universal standards of procedures and merged universes of forensics databases. Future perspectives focus on the automation, AI-assisted pattern recognition and collaboration on a wider plane to enhance precision of analysis and expand on generalization. To sum up, the use of structural deformation-based soil fingerprinting has tremendous advantages in strengthening the forensic soil analysis process, as it can produce better specificity and reliability in geographical sourcing. With the development of new methods of analysis and increased amounts of databases, such approach will become an essential element of contemporary crime science enhancing the results of the investigative work and reinforcing court sessions.

Keywords: Forensic geoscience; Structural geology; Soil fingerprinting; Microstructure; Macrostructure; Fault gouge; Breccia.

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1. Introduction

1.1 Background:

Application of geological materials in the criminal investigations is as old as its history and the most famous examples were observed in the late 19th century (Murray & Tedrow, 1975). Sir Arthur Conan Doyle Having invented the most popular fictional detective Sherlock Holmes, he usually solved crimes by utilizing his knowledge of geology, which demonstrates the possibilities of this field of science in forensic science. The initial case involving a use of forensic geology was however not heard until initial 20 th century when Georg Popp, a German geologist and chemist appeared in the court over an early case (Ruffell & McKinley, 2005). Forensic geoscience has since become an accepted and practical adjunct in law enforcement, the first textbook on the subject (called Forensic Geology) being published in 1975 (Murray and Tedrow, 1975).

Conventionally, forensic geology has integrated the study of soil and mineral within the context of crime analysis in a bid to connect suspects to crime scenes. This usually requires the comparison of soil samples on a body of a suspect on his clothes, shoes or car with a soil sample taken in a particular point (Pye, 2007). Although such an approach has been very effective in most instances, they have a limit. Soil composition can differ dramatically even at short distances, and no specific relationship with a particular area can be considered as absolutely characteristic of the sample collected (Rawlins, Lark, & Aitkenhead, 2015). In addition the composition of soil can be varied by many factors, including weathering, contamination and human activity, which in turn may make the analysis even harder (Sugita & Marumo, 2001). Over the past couple of years, the possibilities of structural geology to perform using a finer and stronger analytical analysis of soil proofs have been increasingly discussed. Rock and other material deformations are studied in structural geology and this knowledge may be employed in detecting peculiarities in soil formed as a result of pertinent geological activities like faulting, folding and shearing. These aspects, which are even retained, at the microscopic scale, can offer a so-called fingerprint of a particular geological environment, giving the possibility of a more accurate and reliable geographical connection of soil samples (Deman, Nys, & De-Vleeschouwer, 2021).

1.2 Scope and Significance:

This review is aimed at surveying how structural geology can be used in a typical and rapidly growing sector within forensic geoscience, which is forensic soil analysis. The main assumption is that such structural deformation characters of soils and the unconsolidated sediments can be big fingerprints, which can be a strong means of geographical matching to the crime scene. In comparison, the structure feature analysis is unlike conventional, relatively-compositional-based soil analysis methods; this way, the soil analysis gives details of geological history of the soil such as the stress and strain of the soil. The data may also be applied to associate a soil sample with a particular location with a far greater level of certainty when compared to the use of compositional analysis.

This approach is important in the sense that it can circumvent some of the shortcomings of the traditional soil analysis. Features of structural deformation are frequently more stable to change than the composition of the soil, and may provide a means of telling apart the soils that are compositionally similar but which may have differing geological histories. This is especially true when there is any disturbance of the soil or when the soil is moved out of place since the structural characteristics are likely to give a significant clue on the origin of the soil.

2. Fundamental Principles of Structural Geology in Soil Forensics

2.1 Soil as Deformable Medium: Soil mechanics and geological stress manifestation

Geologically soil may be thought of as unconsolidated granular material that may be governed by similar laws of mechanics to rocks. But the cohesive force in soil is weak and it is also porous; therefore, soil as a deformable medium is easily deformed due to anthropogenic and natural stresses. Soil mechanics (a sub-section of geotechnical engineering) gives a scientific description of soil behaviour in terms of stress and strain. It is highly valuable in how one envisions the structural aspects seen in soil samples as well as in how one comes to hypothesize how they were formed (van der Pluijm & Marshak, 2004; Pye, 2007).

The reliance of soils on geological stresses (generated by, say, tectonic activity, glaciation, and gravity), may have a specific mark on soil structure. A variety of structural features can form with such stresses compressing the soil, shearing the soil, or folding it. As an example, a glacier may compress underlying soil so a compacted fabric may form (Benn & Evans, 2010). The soil can be sheared by tectonic stresses along fault zones and so lead to the generation of fault gouge and breccia (Sibson, 1977). Simpler stuff like digging a hole may enable the formation of a distinct set of structural characteristics that can be matched with the tool utilized together with the person who created the hole (Morgan, Bull, & Hill, 2006).

2.2 Structural Elements:

Unconsolidated materials are characterized by a number of different structural features, which should be helpful to give some information about the history of the soil. The forensic structural elements of utmost significance comprise of some of the following:

- **Fractures:** These are cracks or breaks on the soil which are brought about by tension or shear. These may either be filled with all sorts of materials, like clay, sand, organic matter and they can also be open. Direction and magnitude of the stresses that formed fractures can be determined by orientation and morphology (Davis & Reynolds, 1996).
- **Shear zones:** zones of high deformation are formed by shearing stresses. They are also defined in terms of diverse characteristics including a decrease in grain size, an orientation of mineral grains and establishment of a unique fabric. It is possible to have shear zones that are brittle and ductile depending on how they were formed (Passchier & Trouw, 2005).
- **Fabric elements:** These are elements which comprise the internal fabric of the soil, e.g. the fabrics of mineral grains, pore location, and sedimentary or pedogenic structures. The fabric of a soil may be primary, i.e. formed at the same time as the soil was deposited, or secondary, i.e. formed after deposition by such processes as compaction, shearing or weathering. Analysis of soil fabric can reveal lots of information concerning the history of the soil concerning its depositional environment, its history of deformation and its history of weathering (Bull, Morgan, & Dunkerley, 2006).

2.3 Microstructural vs. Macrostructural Analysis:

Geologic structural analysis takes place on scales ranging between macroscopic (clear to the naked eye) and microscopic (needs a magnifying lens). This difference is especially relevant in forensic geoscience, because it enables soil evidence to be analyzed more comprehensively.

- **Macrostructural analysis:** The macrostructural analysis is the study of large scale attributes (bedding, folds, faults). The features may be seen either in the field or in hand samples, and they give details regarding the general geological context of a certain place (Ruffell & McKinley, 2008).
- **Microstructural analysis**: Microstructural analysis, however, entails a structural study of smaller scale details, like the patterns of mineral grains, pore distributions, and microfractures. All these characteristics are visible only under the microscope and contain much information on the history of deformation of the soil. The microstructural analysis is an efficient method of soil forensics studies, where particular features may be revealed that cannot be observed on their macroscopic level (Passchier & Trouw, 2005; McKinley & Ruffell, 2007).

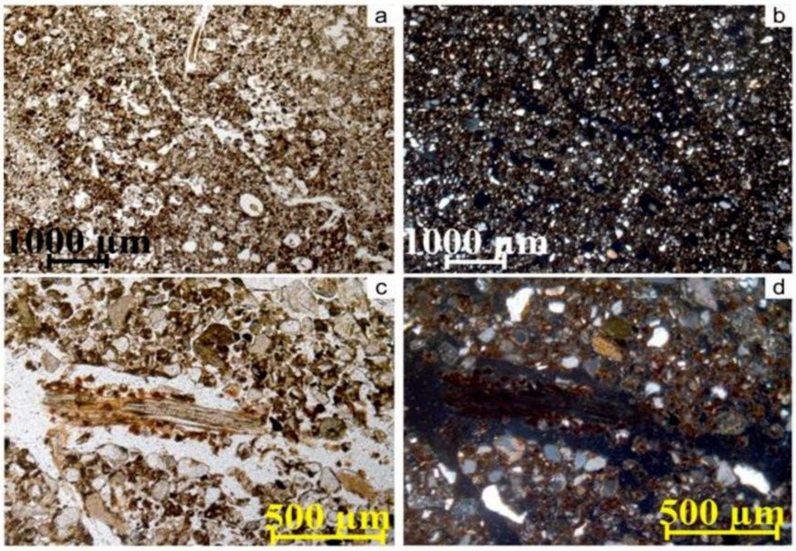

Figure 1: Microscopic view of soil revealing complex structural features critical for forensic analysis.

3. Soil Fingerprinting Using Structural Deformation Features

3.1 Identification of Fault Gouge and Breccia Signatures

Two other types of fault rocks include the fault gouge and breccia caused by the mechanical grinding and crushing of rocks during faulting. They can exist in many geological environments, at scales ranging between large plate margins and small local thrusts and are characteristic of tectonically active areas. Fault gouge and breccia detection of the soil samples may form evidence to strongly support the correlation of a suspect or object to a given area, especially when the area of interest is a known depositional site (Sibson, 1977; Woodcock & Mort, 2008).

3.1.1 Formation mechanisms, mineralogical/textural compositions

Fault gouge and breccia are formed by a process known as cataclasis, which involves the brittle fracturing and comminution of rocks. The main difference between the two is the degree of comminution. Fault breccia is composed of angular pieces of the rock that are larger than 2mm whereas fault gouge is a fine granular clay-rich mud with less than 30 percent visible chunks (Sibson, 1977).The mineralogical composition of fault gouge and breccia is typically similar to that of the parent rock from which they were derived. But in them they can also appear secondary minerals which were created through faulting, including calcite, quartz and clay minerals (Donnelly, Pirrie, & Harrison, 2006).

3.1.2 Microscopic identification:

The identifications of the fault gouge and breccia within a soil sample can be achieved through microscopic analysis. The following characteristics are the main points to consider:

- **Grain size reduction:** The most salient characteristic of fault gouge and breccia is a reduction of the grain size to a large degree compared to the undeformed rock around the breccia. This is because of the great grinding and crushing that takes place during faulting (Passchier & Trouw, 2005).
- **Preferred orientation:** The grain of the minerals in the fault gouge and breccia usually take a preferred orientation; which is the direction of the shear. This is especially so in the platy minerals like that of mica and other clay minerals (Davis & Reynolds, 1996).
- **Cataclastic textures:** A range of cataclastic textures is found in fault gouge and breccia characterized by; angular clasts, microfractures and veins. These texts are evidence of brittle deformations and can be applied to differentiate between fault risks and other soil types (Bull, Morgan, & Dunkerley, 2006).

3.1.3 Macroscopic recognition:

Although microscopic analysis is required in order to positively identify both fault gouge and breccia, a number of macroscopic characteristics can be employed to identify the materials in the field or in ranched or hand samples. These include:

- **Shear surfaces:** Faults are commonly distinguished by the existence of smooth, polished surfaces named slickensides. Such kind of surfaces come about due to the frictional motion of rocks along the fault plane and it is a clear indication of faulting (Ruffell & McKinley, 2008).
- **Comminuted zones:** A fault zone is commonly broken with a broken, highly comminuted zone of rock. The thickness of this zone may be several centimeters or tens of meters and this is where fault gouge and breccia is good to search (McKinley & Ruffell, 2007).
- **Angular clasts:** We stated that the character of fault breccia is the angular clast of a rock. This type of clast may be a few millimeters as well as many meters in size and represents a definite evidence of brittle deformation (Woodcock & Mort, 2008).

3.1.4 Significance in linking to seismically active/tectonically stressed regions

The occurrence of fault gouge or breccia in a soil sample can be a forceful indicator in connecting soil sample to a geographic location. Since these materials are deposited in the course of tectonic events, search could be reduced by focusing on regions which have experienced seismic activity in the past. This may come in handy when other evidence is scarce. To illustrate this, during an investigation on a murder, the evidence of fault gouge on the cloth of the corpse could reveal that the body has been buried in an active tectonic region, and this would limit the search of a secret grave (Lombardi, 1999). A good example of this is the case of the murder of the Italian Prime Minister Aldo Moro that involved the analysis of soil on the clothing of the victim that pointed out at a certain area known to be tectonically active thus indicating the narrowing of the search area that eventually led to the location of the body (Lombardi, 1999)

Figure 2: A visual example of fault gouge, a finely ground material indicative of tectonic activity.

3.2 Use of Foliation, Lineation, and Strain Markers

All of these fabric elements including foliation, lineation, and strain markers have the potential to make some useful data about the history of deformation of a soil. These are usually less conspicuous than fault gouge and breccia but can be equally forensically very helpful. Through close attention to the orientation and stability of these features, one can also recreate the

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stress regime that operated on the ground hence can be utilized to relate the ground to a certain geological setting (Ramsay & Huber, 1983; Davis & Reynolds, 1996).

3.2.1 Development under compaction/shear, planar and linear fabrics

Foliation is a two-dimensional fabric that gets characterized by the favored orientation of prolonged minerals like mica and clay minerals. It is created through a myriad of processes, such as compaction, shear and metamorphism. Foliations that occur in soils are most frequently created by compaction so that all the platy minerals are re-oriented so that they are perpendicular to the direction of the maximum stress. Lineation Linear fabric that can be described in terms of a preferred orientation of the linear elements, e.g. elongate mineral grains, stretched pebbles, or the superposition of two foliations. This is normally formed as a result of shear which makes the linear elements run parallel to the direction of shear (Passchier & Trouw, 2005).

3.2.2 Strain marker identification and deformation recording

Strain markers are things of definite original form that has undergone deformation by the same action which has acted upon the adjacent soil. In determining the extent of strain that has been undergone by soil it is possible to gauge by evaluating the variation of appearance in these objects. Some of the most common strain indicators in soils would be fossils, pebbles and spots of reduction. The characterization of strain markers is an effective method of the deformation history of a soil and used to differentiate among two types of deformation e.g. pure shear, simple shear (Ramsay & Huber, 1983; Pye, 2007).

3.2.3 Quantitative analysis using image analysis/X-ray diffraction

The recent years raised the interest in the applicability of quantitative techniques with regard to soil fabric analysis. Here, techniques like image analysis, and X diffraction permit a more objective and reproducible analysis of soil fabric compared with conventional qualitative methods. Image analysis entails the employment of computer in analyzing digital images of soil thin sections. Programmed to recognize and quantify an array of fabric components, the computer can mark the orientation of mineral grains, the orientation and shape of pores, and fracture distribution (Pye & Blott, 2006). Diffraction method X-ray is a method that can be employed to obtain mineral composition of a soil, and the intensity of preferred orientation of mineral grains (Croft & Pye, 2004).

3.2.4 Correlation with regional geological structures

The eventual aim of the soil fabrics analysis will be to match the fabric measured with that of the local geological structures. The same may be achieved by contrasting the direction of the component fabric that occur in the soil sample to the direction of major geological features in the region like folds, faults as well as joints. In the case where the two have a good correlation, it is going to prove very useful when comparing the soil sample with that area. It can be used especially where the geological history is complicated because it is possible to identify the various geological domains utilizing this method (Davis & Reynolds, 1996; Ruffell & McKinley, 2014)

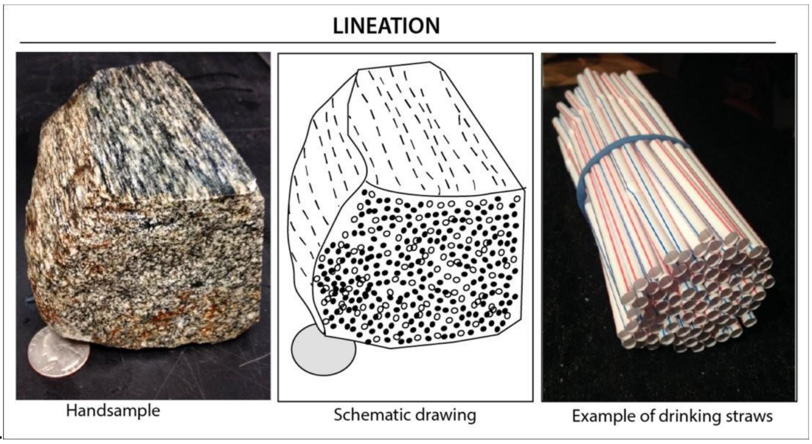

Figure 3: An example of geological lineation, a linear fabric indicating directional stress and deformation.

3.3 Integration of Thin-Section Analysis with Forensic Databases

Petrography or thin-section analysis is an important tool, which geologists used more than one hundred years ago to analyze rock mineralogy and texture. The method is used more and more frequently in the investigation of soils in forensic studies in the recent years. Thin-section can enable the microscopic nature of a soil to be studied in detail and this can produce useful details as regards to origin, history and compositions of the soil (Stoops, 2003; Murphy, 1986).

3.3.1 Methodological advantages of thin-section petrography

There are many advantages of thin-section petrography compared to other soil analysis processes. To start with, it enables the direct study of the fabric of the soil, unlike the other methods (X-ray diffraction, chemical analysis, etc.). Second, it is a non-destructive method that implies that the sampling may be maintained to conduct comprehensive study. Third, it is more affordable and convenient in that it can involve many forensic labs in our society (Fitzpatrick, 2013).

3.3.2 Sample preparation techniques for unconsolidated soils

Thin section preparation of unconsolidated soils is a squeamish business which involves the use of special equipment and special skills. The soil sample is first impregnated using a resin so that the soil is hardened and that it can be cut into thin slices. A glass slide is then placed on the impregnated format of resins that are crumbled using a grinding technique to a thickness of 30 micrometers. A cover slip is then placed on the thin section and polishing done to protect it against damage (Murphy, 1986; Stoops, 2003).

3.3.3 Microscopic features:

Soil thin section reveals a very diverse set of microscopic characteristics which each offer information about the soil history. These characteristics embrace:

- **Mineralogy:** The mineralogy of a soil will be identified based on the identification of various minerals that occur in the thin section. This is possible by using the polarizing microscope to observe the color, forms and optical characteristics of the minerals (Dawson & Hillier, 2010).
- **Texture:** The texture of a soil can be defined as size, shape and arrangement of mineral grains. A soil texture may tell something about depositional environment of a soil, deformation and weathering history of the soil (Pye & Blott, 2006).
- **Fabric:** A fabric of a soil describes how the pieces of soil are arranged, such as the mineral grains and pores as well as the organic matter. Soil fabric may be a primary one, i.e., it was created during soil deposition event, and secondary fabrics, which were generated during the post-depositional processes, like compaction, shearing and weathering (Bull, Morgan, & Dunkerley, 2006).
- **Porosity:** Porosity of a soil is defined as the percentage of empty space everywhere among the mineral grains. A porous soil can give the information on the permeability of such soil, its ability to hold water and resistance to compaction (Schaetzl & Anderson, 2005).
- **Pedogenic features:** Pedogenic features refer to the features formed as a result of soil forming processes e.g. the accumulation of organic matter, translocation of clay, formation of soil horizon etc. Severe pedogenic features may have indications on the age as well as maturity of a soil (Stoops, 2003).

3.3.4 Forensic soil databases: storage, comparison, development challenges

The creation of forensic soil databases is a major step not only to ensuring soil analysis is more punctuated and objective in criminal investigations. The data created in these databases would contain details of the mineralogy, texture and fabric of soils of geographical diversity. This knowledge could subsequently be applied to match soil samples of a crime scene with the ones in the database, which will allow reducing the area to search a suspect or an object (Entwistle et al., 2019).

Nevertheless, a few challenges have to be overcome prior to the widespread use of forensic soil databases. One-Standardized protocols in data collection, analyses and storage of soil- There should be standardized protocols in regard to data collection, analyses, and storage of soil (Jarvis, Wilson, & Kemp, 2012). Second, it requires a big and extensive database that also encompasses a high level of geographical locations and soil types (Rawlins, Lark, & Aitkenhead, 2015). Third, it requires an interface that can facilitate ease of search and comparison of soil data by the forensic scientists (Deman, Nys, & De-Vleeschouwer, 2021). Nevertheless, these issues are overcome by the fact that a study of feel of forensic soil databases is an exciting field of research that could transform the discipline of forensic geo-sciences.

3.4 Discrimination between Natural and Disturbed Soil Structures

Separation and differentiation This is one of the most important issues to solve when working in the forensic soil analysis field identifying the soil structures that have occurred naturally or those that have been developed due to human activities. This becomes especially crucial when the soil has been disrupted because the consequence of this is that the original soil fabric may be covered or destroyed. Nevertheless with close analysis of the soil, one can trace the soil history as well as anything that can have forensic relevance (Morgan, Bull, & Hill, 2006).

3.4.1 Natural processes:

Various processes involving formation of the natural soil structures include:

- **Pedogenesis:** This is the formation of soil, a process that is entailed with the transformation of the parent material through the physical, chemical as well as the biological processes into the soil. As a result of pedogenesis, different horizons of soil are obtained; each of them has its own specific range of properties (Schaetzl & Anderson, 2005).
- **Bioturbation:** It is a type of mixing of soil by living organisms, including earthworms, insects and burrowing animals. There is a number of features that can be formed as a result of bioturbation including mounds, burrows, and tunnels (Vass, 2011).
- **Weathering:** This is a breaking down process of soil through physical, chemical, and biological processes. The effects that can be formed through the process of weathering include fissures, cracks and clay skins (Pye, 2007).
- **Natural compaction:** This is a kind of soil that has been put under pressure by the weight of the materials that cover it, like the glaciers, water or other residue. There is also the possibility of natural compaction resulting in the creation of a normal compacted fabric with diminishing porosity (Benn & Evans, 2010).

3.4.2 Anthropogenic disturbances: excavation, compaction, tilling, construction

The anthropogenic disturbances are triggered by the humans, e.g.:

- **Excavation:** It means the process of digging under the soil and it may produce an array of features including pit, trench, and grave. The size and the shape of these features may give details of the tool employed and the individual, who did the digging (Morgan, Bull, & Hill, 2006).
- **Compaction:** Here, soil is densified by the weight of the vehicles or equipment or people. It can cause demolition of the original soil fabric with formation of a compacted layer (Certini & Scalenghe, 2011).

- **Tilling:** This is done by preparing the soil to practice agriculture and this mechanism includes the acts of mixing and turning the soil. Several features may be formed by tilling i.e. plow marks, furrows, and ridges (Schaetzl & Anderson, 2005).
- **Construction:** It is the stage in which the structures are constructed on the ground and it may entail a number of activities, e.g., grading, filling, excavating the ground. Such activities may greatly influence the soil and may form many features which are of forensic value (Certini & Scalenghe, 2011).

3.4.3 Identifying forensic alterations vs. natural deformation

The first indication of the difference between the natural and disturbed soil structures is by observing the signs of features that do not match with the natural soil forming processes in the location. To give an example, the sharp linear divide between two soil types is possible evidence of a grave, or even a pit. On the same note, an indicator of a road or a path may be the availability of compacted layer of high bulk density. With the help of close inspection of the soil on such and other characteristics, one can see any disturbed area and in turn it is feasible to determine the chain of events that occurred due to the disturbance (Morgan, Bull, & Entwistle, 2010).

3.4.4 Multi-proxy approach combining structural, chemical, mineralogical, biological indicators

The most successful solution to the problem of differentiation between natural and disturbed soil structures is a multi-proxy approach that refers to the combination of all the measures of the following indicators, including structural, chemical, mineralogical, and biological ones. Structural analysis could be used to give the history of the soil deformation whereas chemical analysis could be used to give the contents of the soil. Mineralogical analysis may give the origin of the soil and biological analysis may give the information on the organisms that have lived in soil. Using these several strands of evidence in conjunction, one can build a richer and more truthful picture of the history of the soil and detect any evidence that could be of forensic value (McKinley & Ruffell, 2007; Farsani & Shokri, 2020). There is also combined palynology (pollen and spores) and geology that has come to be very useful when working on forensic cases (Mildenhall, Wiltshire, & Bryant, 2006; Horrocks & Walsh, 2007). Table 1 is a summary of the main structural deformation features often available in forensic soils, the qualities of these features and their forensic importance.

Figure 4: An example that would show various types of anthropogenic disruption of landscapes capable of heavily transforming natural soil architectures and establishing them with forensically identifiable properties.

Comparative Table of Soil Deformation Features

The table provided below represents the summary of the important characteristics of structural deformations that are observed in soil, common features of these deformations and their role in emphasizing differences in forensics. This is a ready reference guide of how each feature adds up to the fingerprint of a soil sample.

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Table 1: Comparative Analysis of Structural Deformation Features in Forensic Soil Analysis

Structural Feature	Characteristics	Microscopic Identification	Macroscopic Recognition	Forensic Significance
Fault Gouge	Very fine-grained, clay-rich material; intense grinding.	Extreme grain size reduction, preferred orientation of clay particles, cataclastic textures.	Soft, pulverized zones, often clay-like; distinct shear surfaces.	Strongly indicates origin from seismically active or tectonically stressed fault zones.
Fault Breccia	Angular to sub-angular rock fragments in a finer matrix.	Angular clasts, evidence of fracturing and grain rotation.	Visible angular fragments (jigsaw-fit texture) within a fine matrix.	Indicates brittle deformation along fault zones, linking to specific geological environments.
Foliation	Planar fabric (e.g., preferred alignment of platy minerals, aggregates).	Aligned platy mineral grains (e.g., clays), elongated particles forming layers.	Visible layering or parallelism of components, particularly after compaction.	Reveals directional stress (compaction, shear); characteristic of pedogenic or tectonic environments.
Lineation	Linear fabric (e.g., alignment of elongated particles, intersection of planar features).	Elongated mineral grains or stretched features showing preferred orientation.	Linear streaks, grooves, or alignments visible on surfaces or cross-sections.	Indicates direction of shear or flow; links to specific deformation history.
Strain Markers	Deformed objects within the soil (e.g., grains, ooids, fossils).	Measurable deformation of identifiable objects, changes in shape/orientation.	Visibly flattened or elongated pebbles, shells, or other inclusions.	Quantifies magnitude and direction of strain, useful for high-strain zones.
Anthropogenic Compaction/Disruption	Increased density, altered porosity, mixed horizons, foreign materials.	Irregular grain packing, micro-fractures, disturbed natural fabrics, exotic particles.	Track marks, disturbed layering, unusual density variations, presence of man-made debris.	Key for distinguishing criminal activity (e.g., burial sites, vehicle tracks) from natural processes.

4. Case Studies and Applications in Criminal Investigations

4.1 Homicide Investigations:

Soil evidence can also be used in the investigation of a homicide to prove the connection between a suspect and a clandestine grave. This can be great evidence of a suspect in a crime when he has soil on his/her clothing, shoes, or vehicle similar to what is found in the burial site. In these instances structural analysis may prove especially beneficial since, it can be applied to determine the special attributes in the soil that cannot be detected by the naked eye. Indicatively in one of the cases in the United Kingdom, the suspect was brought into court because analysis of soil samples in the spade showed the presence of a rare mix in minerals and microfossil combination that was only present at a clandestine grave (Ruffell, 2010). This fact was vital in achieving a conviction.

One of the most outstanding case studies, which exemplify the strength of this practice is the case which concerns the killing of a child in northern England (Ruffell, 2003). The body of the victim had been dealt with in a shallow grave in a secluded forest. The police had their suspect, yet they did not have the physical evidence that would help to tie him into the criminal deed. A forensic geologist was brought in to the test the soil in the boots of the suspected person and the body at the place of burial. The investigation showed that the footwear had the excellent match of the soil which contained a special mixture of minerals and rock morsels that were also found in the grave. The geologist also found several microscopic profiles of the soil concerned like microfossils and pollen grains which were peculiar to the woodland where the body was discovered. This evidence that was used in court played a major role in the conviction of the suspect as killing a human being.

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4.2 Trafficking Investigations:

Trafficking investigation can also be done using soil evidence in order to determine the source of the illegal product like drugs, weapons, and endangered species. As it would be possible to analyze the soil on these materials, it is possible to know their geographical origin, which in its turn can allow knowing what routes are used as the trafficking routes and who are engaged in it. The study of seized cacti depicted in a case by soil sample taken at the base of the cacti showed that it was made up of a special mix of minerals and volcano glass present in an exclusive location of Mexico (Murray, 2004). This was the evidence to track the origin of the cacti and to provide prosecution of the traffickers.

4.3 Environmental Crime:

Forensic geology is more and more applied to the exploration of environmental crimes, including illegal heavy dumping and excavation. Further traces of the source of dumped materials may be told by examining the soil in a suspected dump site to know the type of materials that have been dumped and tracing it back to origin. Case in point, in an instance whereby hazardous waste was illegally disposed of, the soil tests taken at the dump site showed a distinct mixture of chemicals and heavy metals which was never seen but at a certain industrial plant. This was the evidence that was used to indict the company that dumped and compel them to clean up the spot.

The story of a strong case study in the United States illustrates the success of the forensic geology as part of the environmental crime investigation (Pye, 2007). In this case, there was the illegal disposal of thousands of tires in a secluded and a conserved wetland site. The tires posed a major threat to the environment since they were taking out the toxic chemicals to the soil and water. The officials were not given any clue of the dump culprit. A forensic geologist was subsequently called in to analyze the soil and sediment samples in the dump site. It was discovered that it contained a special kind of clay that was available in a certain quarry, far off in hundred of miles. The geologist was also able to perceive several microscopic characteristics in the soil like the diatoms and other microorganisms that were characteristic of the wetland environment. This fact, along with an in-depth research into records of the quarry in terms of sales, directed the authorities to a trucking company that was contacted to haul the tires to a recycling center. The tires had been thrown in the wetland illegally so as to avoid the cost of recycling. The forensic geologist had to summon important evidence which helped in convicting the company of crime against the environment and help them pay direct costs of cleaning up the site.

4.4 Challenges and Limitations:

Although there are numerous achievements connected to the use of this technique, the use of structural geology in forensic analysis of soil is not free of challenges and limitations. The possibility of contamination is one of the major challenges. Other materials can easily contaminate soil samples thus making it hard to detect the original soil fabric. The mixed soil types are the other challenge. A soil sample can in most occasions be a combination of two or more soil types which may complicate the interpretation of the analysis carried out. Finally, the interpretation of structural features in soil can be complex and requires a high level of expertise. It is important to remember that soil analysis is just one tool in the forensic toolbox, and it should always be used in conjunction with other lines of evidence (Morgan & Bull, 2007).

Forensic Soil Analysis:

To illustrate the distinct advantages and challenges of various forensic soil analysis methods, particularly highlighting the unique contributions of structural geology, the following charts provide a comparative assessment based on expert opinion and current capabilities. Figure 5 presents a radar chart comparing the discriminatory power of different analytical techniques across key criteria, while Figure 6 evaluates their readiness for widespread adoption in forensic laboratories.

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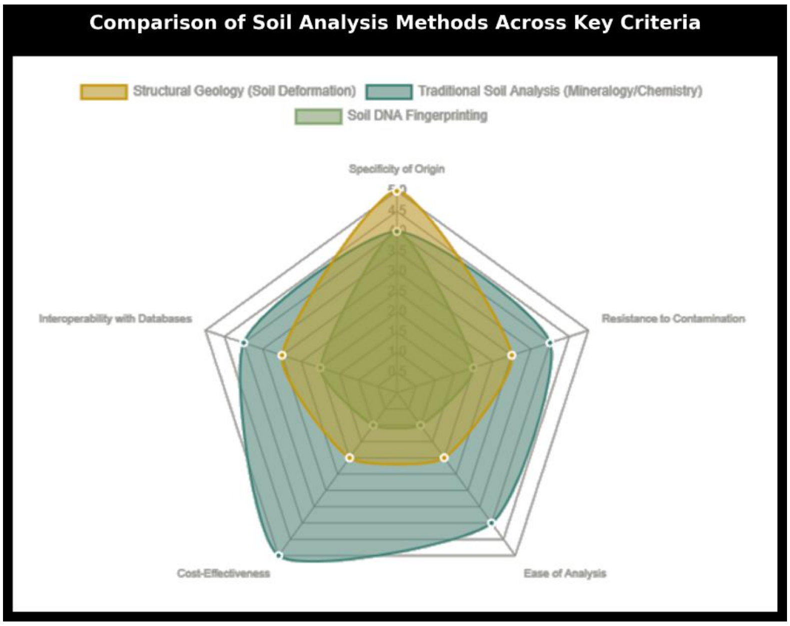

Figure 5: Comparative Assessment of Forensic Soil Analysis Techniques: Radar Chart Showing Discriminatory Power Across Key Criteria

The radar chart above assesses different forensic soil analysis techniques based on several key criteria, on a scale of 0 to 5. Structural geology excels in providing high specificity of origin due to its direct link to unique geological stress fields, offering a level of detail not easily matched by other methods. Traditional mineralogy and chemistry provide good all-around performance, particularly in ease of analysis and cost-effectiveness, as they are well-established. Soil DNA fingerprinting, while offering strong discriminatory power, currently faces challenges in ease of analysis, cost, and database interoperability, primarily due to the complexity of microbial communities and the nascent stage of comprehensive soil DNA databases. This chart highlights that while structural geology provides highly unique clues, it often requires specialized expertise and can be more complex to integrate broadly at present.

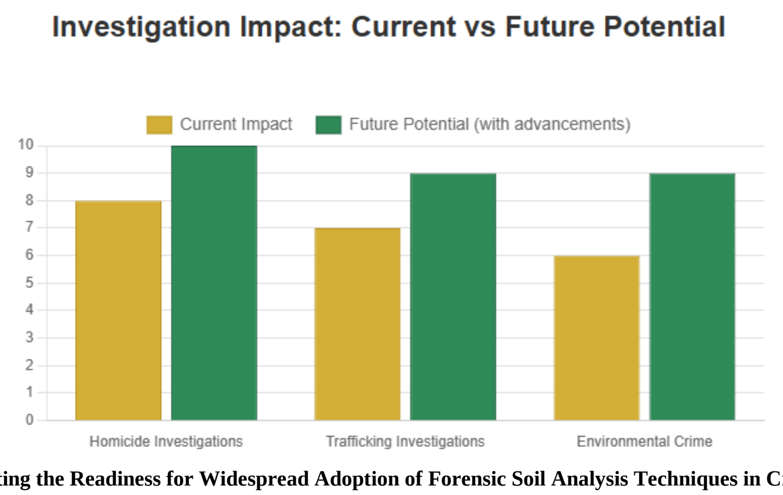

Figure 6: Bar Chart Evaluating the Readiness for Widespread Adoption of Forensic Soil Analysis Techniques in Criminal Investigation Types

The bar chart above illustrates the current impact and future potential of forensic geoscience in various criminal investigation types, on a scale of 0 to 10. Homicide investigations currently benefit significantly from soil evidence, particularly in linking suspects to burial sites or crime scenes, and this impact is projected to increase further with advancements in structural analysis. Trafficking investigations also see substantial current impact, especially in tracing the geographic origin of illicit goods. Likewise, it has a great future potential because more advanced methods of detecting clandestine routes are being created. Although environmental crime investigations have a certain existing capability of using forensic geoscience to detect illicit activities such as dumping, the untapped potential of forensic geoscience in investigations to detect and quantify disturbed volumes remains very high as the analytical methods are refined. The chart highlights the increased usefulness of forensic geoscience throughout the criminal justice space.

5. Future Directions and Research Gaps

5.1 Analytical Technique Advancements:

One of the most promising directions in the development of forensic geoscience is the construction of new methods of analysis. In recent years, the use of automated methods, e.g. automated mineralogy and image analysis, to analyse soil samples, has become an area of increasing interest. The methods can make the analysis of soil quicker, objective, and reproducible. Moreover, an increasing number of people are interested in artificial intelligence (AI) and machine learning (ML) to process soils information. New and stronger approaches to soil fingerprinting may arise as new data can be learned and discovered in a machine that was invisible even to the human eye and thus, new and interesting developments AI and ML-wise could be established.

5.2 Standardized Protocol Development:

The poor standardization of protocols in the field of collection, analysis, and interpretation of the data on the soil is one of the greatest challenges of forensic geoscience. It is hard to compare studies with one another through this lack of standardization and even prove the reliability of soil evidence in the court. A significant step to advancing a more solid and steady instrument of soil analysis is the creation of the standardized protocols in criminal investigation. Take a positive step in this direction, a Committee on Forensic Sciences E30 of the ASTM International presently working on some standards of forensic analysis of the geological materials.

5.3 Forensic Database Expansion:

Another step which would make soil analysis an even more effective instrument in criminal investigation is the development of comprehensive forensic soil databases. These databases ought to include information on mineralogy, texture and fabric of soils at various geographical locations and geological environments. Development of the available databases, e.g. the USDA Web Soil Survey toward the individualization of the contained data concerning the soil microstructure and the mineralogy would contribute to the research area.

5.4 Interdisciplinary Collaboration:

Successful practice of structural geology in the field of soil analysis in forensics is associated with a strong degree of collaboration amid disciplines. Other sets of people that contribute and can be used in the development and application of such methods include structural geologists, soil scientists as well as forensic practitioners. Structural geologists are in a position to render any knowledge about the deformed rocks and soils whereas soil scientists can offer the related knowledge about the formation and character of soils. The forensic practitioners are in a position to offer expertise information on the evidence collection and interpretation in criminal investigation. Among those different disciplines, collaborative efforts can be made to deal with the evidence in the field of the criminal justice system so that the soil evidence can be put into practice in every way possible (Ritz, Dawson, & Miller, 2009; Pirrie, Ruffell, & Dawson, 2013).

6. Conclusion

The review has shown that the influence of structural geology in forensics soil analysis is indeed valuable. The forensic geoscientist could use forensic geoscience to gain a more detailed and stronger understanding of the soil evidence than could be generated with traditional compositional analysis alone, by analyzing features in the structure deformation of soils and unconsolidated sediments. The detection of rock characteristics like fault gouge, breccia, foliation, lineation as well as strain markers has the potential of giving a unique fingerprint of a particular geological environment thus providing more operationally precise and reliable geographical provenancing of soil samples. The combination of thin-section analysis with forensic databases as well as creation of standardized protocols and advanced analytical methods will also increase the strength of this tool.

The use of structural geology in criminal justice system through the analysis of soil can be influential in forensic soil analysis. As these methods offer more solid and dependable evidence, they are able to increase the potential of the investigating process, resulting in the suspected criminal, finding covert graves, and tracing illegal substances. Analysis of the soil evidence which may have been conducted through application of structural geology methods may be introduced in the court with a greater advancement of scientific accuracy and this may contribute positively towards ensuring that justice prevails.

To sum up, forensic geoscience, and, specifically, the exercise of structural geology to study soils, is a very valuable part of criminalistics these days. With our increasing knowledge of the intricacies behind soil deformation and with the advent of new methods of analysis, the potential importance of soil evidence in criminal investigation is only expected to increase. Through the interdisciplinary approach that unites the experience of the structural geologists, soil scientists, and forensic practitioners, we will be able to use such a powerful tool to its full potential in the quest of justice.

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