

Soil is everywhere, easily transferred and incredibly difficult to completely remove. It adheres tenaciously to treads, cuffs and crevices. Crucially, no two places on Earth have exactly the same soil composition. While large areas might share broad similarities, the specific combination of components at a particular location, a backyard, a field corner, a riverbank - acts as a unique, albeit complex, fingerprint. This fundamental principle underpins the entire field.

The science in the soil: Deciphering the Earth's code

Forensic soil scientists are geological and biological detectives. Their analysis involves a multi-pronged approach, examining the physical, chemical, mineralogical and biological components of a sample;

1. Physical and microscopic examination:

Physical and microscopic examination are the initial, crucial steps in forensic soil analysis. These techniques are often performed first because they are non-destructive, meaning they don't alter the sample, leaving it intact for more advanced, and potentially destructive, chemical or biological tests later. The goal is to establish a unique "profile" for the soil based on its observable characteristics.

- ✓ **Colour:** Assessed using standardized charts (Munsell soil colour charts) under controlled lighting. Variations hint at mineral content and organic matter.
- ✓ **Texture:** The relative proportions of sand, silt and clay particles, determined by feel or laboratory sedimentation. Texture influences how soil adheres and transfers.
- ✓ **Particle size distribution:** Precise measurement of particle sizes using techniques like laser diffraction or

sieving. PSD profiles can be highly distinctive.

- ✓ **Microscopy:** Low-power stereomicroscopy identifies larger inclusions (seeds, fibres, insect parts, paint chips, glass fragments). High-power light microscopy and Scanning Electron Microscopy (SEM) reveal mineral shapes, surface textures and finer details.

2. Mineralogical analysis: Mineralogical analysis is a core component of forensic soil science, focusing on the identification and quantification of the minerals that make up the inorganic fraction of a soil sample (Dawson and Hillier, 2010). Since mineral composition is highly dependent on a region's geology, it's a powerful tool for linking a suspect or object to a specific location.

- ✓ **X-Ray Diffraction (XRD):** The gold standard. Bombards the sample with X-rays; the resulting diffraction pattern acts like a unique "signature" revealing the specific crystalline minerals present (e.g., quartz, feldspar, clay types like kaolinite or smectite). The relative abundance of these minerals is often crucial for comparison.

- ✓ **Polarizing Light Microscopy (PLM):** Allows identification of minerals based on their optical properties (refractive index, birefringence, cleavage) when viewed under crossed polarizers. Skilled analysts can identify dozens of minerals in a single sample.

3. Chemical analysis: Chemical analysis of soil involves a range of techniques to identify the elements, compounds, and other chemical properties within a soil sample. This is crucial for establishing a chemical "fingerprint" that

can link a soil sample from a suspect to a crime scene (Marumo, 2003).

- ✓ **Elemental composition:** Techniques like X-Ray Fluorescence (XRF) or Inductively Coupled Plasma Mass Spectrometry (ICP-MS) detect and quantify trace elements (e.g., heavy metals like lead or arsenic or nutrients like phosphorus and potassium) (Coccatto, 2017). Geographic variations in underlying geology or pollution can create distinct elemental "signatures."
- ✓ **Organic chemistry:** Analysis of specific organic compounds like petroleum hydrocarbons, pesticides or unique plant-derived biomarkers using Gas Chromatography-Mass Spectrometry (GC-MS).

4. Biological components: Biological components in forensic soil science refer to the living and once-living materials found within a soil sample (Wescott, 2018). These components are valuable in criminal investigations because they are highly diverse and specific to a particular location, providing a unique biological signature.

- ✓ **Palynology (Pollen and spores):** Pollen grains are incredibly durable and species-specific. Their presence can link soil to a particular vegetation type or even season.
- ✓ **Diatoms:** Silica-shelled algae found in water bodies. Specific diatom assemblages in soil can indicate proximity to a particular lake, river or estuary. Crucial in drowning cases.
- ✓ **Microbiology:** DNA analysis of soil microbial communities is an emerging frontier. The complex mix of bacteria and fungi can be highly location-specific.

- ✓ **Plant fragments and phytoliths:** Microscopic silica bodies formed in plant cells, specific to plant families or genera.

Applications in criminal investigations

Forensic soil science is a specialized field that uses the unique properties of soil to help solve crimes (Terribile *et al.*, 2024). It relies on the principle that soil from different locations has distinct physical, chemical and biological characteristics, making it a valuable form of trace evidence.

- ✓ **Link a suspect to a crime scene:** Soil samples found on a suspect's clothing, shoes, tools or vehicle can be compared to soil collected at the crime scene. A match can provide strong evidence that the suspect was present at the location. For example, if a suspect's boots have a unique soil mixture of clay and volcanic ash that matches the soil at a burglary site, it places them at the scene.
- ✓ **Disprove an alibi:** If a suspect provides an alibi claiming to have been in one location, but soil evidence on their belongings matches a different, more relevant location (e.g., the site where a body was buried), it can invalidate their story. This is particularly useful in cases where the suspect denies ever being near the crime scene.
- ✓ **Identify geographic origin:** Soil composition can be used to determine the geographic origin of an object or individual. By analysing the types of minerals, pollen and microorganisms present, forensic scientists can narrow down the potential location from which the soil originated. This can be critical in cases involving unidentified bodies or objects transported from another area.

- ✓ **Locate buried evidence or graves:** Soil disturbances can indicate a clandestine grave or a location where evidence has been buried. Forensic geologists use techniques like ground-penetrating radar (GPR) and magnetometry to identify anomalies in the soil profile that suggest recent digging. These methods can help law enforcement locate buried bodies, weapons or other crucial evidence.
- ✓ **Reconstruct events:** The presence of soil on objects in an unusual context can help reconstruct the sequence of events at a crime scene. For instance, soil on a vehicle's undercarriage that matches soil from an off-road location can suggest the vehicle was driven through that area, which might be a critical detail in a hit-and-run investigation.

The forensic workflow: From crime scene to court roomy

The forensic workflow for soil evidence follows a methodical process from the initial collection at the crime scene to its presentation in court. This process ensures the integrity of the evidence and the reliability of the scientific findings.

1. **Scene investigation and collection:** The chain of custody begins here. Soil samples are meticulously collected:
2. **Control samples:** From relevant areas at the scene (Where the victim was found, entry/exit points, alibi locations).
3. **Questioned samples:** Recovered from suspects/victims (shoes, clothing, vehicle pedals/wheel wells, tools, under fingernails).
4. **Packaging:** Collected in clean, sealed containers to prevent contamination or moisture-related changes. Precise location documentation is vital.

5. **Laboratory analysis:** Samples undergo the battery of tests described above, chosen based on the case context. The goal is to build a comprehensive profile for each sample.

6. **Comparison and interpretation:** This is the critical phase. Profiles of questioned samples are compared to control samples. The scientist asks:

- ✓ Do the samples share significant mineralogical, chemical and biological characteristics?
- ✓ Are there any exclusive components present in both?
- ✓ How common or rare are the shared characteristics in the wider region?
- ✓ Could the questioned sample have originated from the crime scene location or is it clearly different?

7. **Reporting and testimony:** The forensic soil scientist produces a report detailing methods, findings and interpretations. Crucially, they testify in court, explaining complex science in understandable terms, presenting the significance (or lack thereof) of the soil evidence and facing cross-examination. They avoid overstating conclusions; soil evidence is typically associative ("consistent with originating from...") rather than definitively pinpointing a single source, unless highly unique markers are present.

Cases written in earth: Real-world impact

(Taken from: Forensic Geology, by Raymond C. Murray and John C.F. Tedrow (1992))

First criminal case using earthen materials as evidence: In 1904, forensic scientist Georg Popp used soil and mineral evidence to solve the murder of Eva Disch in Frankfurt, Germany. A handkerchief found at the scene contained traces

of coal, snuff and the mineral hornblende. The suspect, Karl Laubach, worked at a coal-burning gasworks and a gravel pit. Popp discovered similar traces of coal and hornblende under Laubach's fingernails and also confirmed he used snuff. Most critically, Popp analysed soil from Laubach's trousers. He found two distinct layers: a lower layer that matched soil from the crime scene and an upper layer containing mica grains that matched the path leading to Laubach's home. This evidence proved Laubach had been at the murder scene and then walked home, a conclusion he could not deny. Confronted with Popp's findings, Laubach confessed. This case marked the first documented use of forensic geology in a criminal investigation.

Traces of red face powder beneath a suspect's fingernails (1912): In 1912, Dr. Edmond Locard used forensic science to solve the murder of Marie Latelle in Lyons, France. The primary suspect, her boyfriend Emile Gourbin, had a seemingly solid alibi. Locard examined scrapings from under Gourbin's fingernails and found tissue that could have been from the victim. More importantly, the tissue was covered in a pink dust. Locard analysed this dust, identifying it as a unique blend of rice starch, bismuth, magnesium stearate, zinc oxide and Venetian red. This composition matched the custom-made face powder Marie Latelle used, which had been prepared for her by a local druggist. Due to the distinctive nature of the powder at the time, this evidence was crucial and led to Gourbin's confession. This case highlighted the value of trace evidence in criminal investigations.

Grains of Merritt Sand point to another location 12 miles away (1925): In 1925, forensic geologist Edward Heinrich used his geological knowledge to assist in the murder investigation of Mrs. Sideny d'Asquith. When an ear belonging to the dismembered victim was found in a marsh near El Cerrito, California, Heinrich discovered

that the sand grains on the ear were not from the marsh. He concluded that the body had been placed somewhere else initially and the ear had been moved later. By analysing the size, composition and minimal salt content of the sand grains, he deduced they came from a location where a river or creek entered the ocean. Based on this, he pinpointed Bay Farm Island, near the mouth of San Leandro Creek, as a likely spot. A search of the area uncovered the rest of the body buried under a drawbridge. Although the case remains unsolved, Heinrich's skillful use of forensic geology was a groundbreaking introduction of the science to the United States.

Challenges and limitations: Reading the earth's fine print

Forensic soil science, while a powerful tool in criminal investigations, is not without its challenges and limitations. The "fine print" of the earth's composition can be difficult to read, and a number of factors can complicate the analysis and interpretation of soil evidence.

The inherent variability of soil: Soil is a naturally heterogeneous material. Its composition can change dramatically over very short distances, both horizontally and vertically. This spatial variability means that a soil sample collected from a suspect's shoe might not be a perfect match for a sample taken just a few feet away at a crime scene, even if the suspect was undoubtedly there. Forensic scientists must account for this variability in their sampling strategy and in the interpretation of their results.

Contamination and integrity: The integrity of soil evidence is paramount, but it is highly susceptible to contamination. Cross-contamination can occur if proper protocols are not followed during collection, packaging, and analysis. For instance, a sample from a suspect's boot could be contaminated with soil from the collection site, or a lab tool could transfer material

from one sample to another. Additionally, soil on a suspect's clothing or vehicle might be a mixture of soils from various locations they have visited, making it difficult to pinpoint the exact source.

The lack of standardized protocols and databases: Unlike DNA or fingerprints, there is a lack of universally standardized protocols for forensic soil analysis. Different labs may use different techniques, and there is no single, comprehensive national or international database of soil profiles for comparison. This makes it challenging to compare results across jurisdictions and can limit the ability to confidently determine the geographic origin of an unknown sample.

The challenge of "Individualization": While soil can provide strong class evidence (e.g., this soil is from a volcanic region), achieving a definitive individualization (e.g., this soil came from this specific spot and nowhere else) is extremely difficult. A match between two soil samples typically means they share a common origin, but it is rarely possible to say with 100% certainty that they are identical. The strength of the conclusion depends on the rarity and uniqueness of the characteristics found, such as a combination of specific minerals, pollens, or microorganisms.

Environmental factors and degradation: Soil evidence is not static; its properties can change over time. Weathering, microbial activity, and human intervention can alter the physical, chemical, and biological components of soil. For instance, a heavy rainstorm could wash away a distinctive top layer of soil, or a new layer of sediment could be deposited, complicating a comparison. The degradation of biological components like DNA in microorganisms is also a concern, as it can make analysis more challenging, especially in older samples.

The "Invisible" nature of soil evidence: Because soil can be nearly invisible to the naked eye,

particularly fine-grained material, investigators may be unaware of its presence. This can lead to missed opportunities for evidence collection at a crime scene. Conversely, a suspect may be unaware they have collected soil evidence on their person or property, which is one of the reasons it is such a valuable form of trace evidence. However, this also means that the decision to collect soil samples relies on the vigilance and training of investigators, which may not always be consistent.

Conclusion

Forensic soil science exemplifies how seemingly insignificant traces can hold monumental significance. A smear of mud, a dusting on a boot, a grain trapped in a tire tread - these are not just dirt; they are fragments of a landscape, carrying within them a story waiting to be decoded. By applying rigorous geological, chemical and biological principles, forensic soil scientists give voice to the silent witness beneath our feet. They transform the earth itself into a powerful ally in the pursuit of justice, reminding us that no one moves through the world without leaving behind or carrying away, a tell-tale piece of the ground they walked upon. In the intricate puzzle of a crime, the soil may well hold the key piece that snaps everything into place. *The dust, as the saying goes, never lies, we just need the science to understand its testimony.*

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