30. Spatial distribution of soil geochemistry in geoforensics

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Soil geochemistry may be applied in the science of geoforensics in two ways: to establish the provenance of samples and to inform the question of sample variability. Tellus data can assist in answering on a broad scale the provenance question, 'where may this sample have come from?' Although the Tellus data are too widely spaced for precisely locating the source of a sample, the spatial variation in geochemistry may exclude areas where a sample of unknown origin came from.

Using soil in geoforensic investigations

Geoforensics is 'the application of selected geoscience techniques to criminal (domestic, international, terrorist, humanitarian, environmental, fraudulent) investigations of what happened, where and when it occurred and how and why it took place' (Ruffell and McKinley, 2008). The discipline has been divided into two overlapping areas of research and practice (Pirrie, 2009): trace evidence and search/location. Trace evidence analysis is usually conducted in order to establish the characteristics of samples from (i) a scene or locus, (ii) control or alibi locations (both being known) and (iii) a suspect item of which the origin is unknown and that commonly might be a vehicle, footwear, clothing, tools or suspected fake items.

Soil mineralogy and microbiology are used to these ends but are never used in a direct attempt to 'match' soil samples. Although each soil is a unique mixture of organic and inorganic materials, there is always the possibility of two or more different locations having soils that our current methods of analysis cannot distinguish. For this reason, the forensic pedologist employs the exclusionary principle (Morgan and Bull, 2007). This states that the mineral and organic characteristics shown by samples from the scene of crime and the suspect are more similar than any control samples or those in a database, thus excluding all possibilities except that they have the same origin. Trace evidence (for example on footwear, clothing or vehicles) and the scene of crime are sampled at a far more detailed scale than soils and sediments collected in regional soils surveys. This precludes use of such regional databases in many forensic scenarios; it is a simple matter of differences of scale. Nonetheless, for a regional picture of the variation in soil geochemistry, databases

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such as Tellus are valuable, and for certain types of forensic enquiry, such as limiting the possible locations of origin, they can be very useful, as we show below. Soil and sediment are transferable, meaning that if every contact leaves a trace (Locard's Exchange Principle; Murray, 2004), the variability in such Earth materials may assist law enforcement and the legal system in establishing where the accused or the victim may have been (provenance).

Two commonly asked questions of search and scene samples are 'where did this soil come from?' (the question of *provenance*) and 'what is the likelihood of another soil, with identical characteristics, coming from another place?' (the question of trace evidence *variation*). Some answers to both questions may be derived from a consideration of baseline variations in soil and sediment properties, typical of which may be querying a spatial database. Geographically spread geochemical data such as the soil and stream sediment analyses in the Tellus and Tellus Border maps and data comprise such information. In considering how the Tellus data may be used in the forensic arena we assess first how databases have been previously used and secondly what the Tellus data comprise in light of this.

How databases have been used in geoforensics

Although limited in number, previous publications on the use of databases in geoforensics provide a background against which to discuss the use of the Tellus data. As is often the case with anecdotal accounts of criminal cases, an early use of databases is based on a secondary account. Block (1958) recounts how Professor Oscar Heinrich (a private investigator who also taught criminalistics courses at the University of California, Berkeley) was asked to assist in the 1923 search for a missing person, presumed dead. The supposed victim was known as both Mrs Sidney d'Asquith and Mrs J.J. Loren, her alias being a clue to her colourful and complex lifestyle. Not far from her last known location, a severed ear and some fragments of scalp were discovered in a marsh (near El Cerrito, California), prompting an intense police search of the area. This found nothing, at which point Heinrich was brought in.

Heinrich had a great gift for the recovery of trace evidence (Murray, 2004): in this case some grains of sand in the ear that were not comparable to the black mud of the marsh. Using the as yet unpublished methods of quartz grain surface textures, Heinrich concluded that the grains originated in an estuarine environment. He then consulted drift geological maps of the area, the paper equivalent of a spatial database in in 1923, noting estuaries in order of proximity to the find location of the ear. The closest and most likely (in Heinrich's view) was a place named Bay Farm Island, where a police search subsequently discovered the remains of Mrs d'Asquith's body. No suspect was apprehended, but Heinrich had shown the first use of a spatial database in directing a search for a murder victim.

Murray (2004) also shows the usefulness of geological maps in understanding the context of where scene and suspect samples have come from, as well as suggesting locations for the origin of unknown samples. One example provided is the abduction and murder of the millionaire Adolph Coors. The succession of mud/soil/sediment in the inside of the bumpers of the suspect's car reflected the geology and soil maps along the route he was accused of taking as he drove across the USA. Morgan and Bull (2007, p. 78) state: 'Localised databases constructed from the analysis of samples from exclusion locations may be adequate.' The most comparable work to this is that of Pye and Blott (2009), who used soil geochemistry to demonstrate how soil of unknown origin (say on a suspect, or indeed a victim's body) in England could potentially be limited to coming from some locations and not others.

Lark and Rawlins (2008) pose a question that is equally apposite to the current work and also use soil geochemistry as their example database. One of their main challenges is how to deal with as many variables as those provided by an elemental database with multiple locations and (as in their example) each with over 50 elements analysed: a point considered below. Their second point is the difficulty of comparing analyses of forensic samples, which may comprise small quantities of soil (less than 1 g), requiring inductively coupled plasma (mass spectrometry/atomic emission spectroscopy), ICP (MS/AES) analysis, with the analyses of much larger samples conducted by the different method of X-ray fluorescence (XRF). Lark and Rawlins (2008) note, however, that the only database that may be suitable for such suspect-to-location comparisons is the Tellus survey.

McKinley (2013) follows this contention with a consideration of how such data may be used, using the theoretical geochemistry of material sampled from a suspect vehicle (a dump truck used in environmental crime) to pinpoint a likely location. McKinley (2013) summarises the other sorts of databases that could be used in our two main areas to be considered – provenance and variation – and poses the main question of the two applications set out below: 'is the digital database suitable in forensic investigations?' Based on the two case studies presented below, the answer is a definitive 'yes', albeit with the caveats of local (metre to kilometre) soil variation, analytical methods and differences in sample size between suspect (often small) and scene (effectively unlimited).

Provenance: using Tellus databases for search and trace evidence location

In 2013, three men were stopped by a police checkpoint on the Northern Ireland/Republic of Ireland border. In the boot of their car, materials (wires, wire drums, fertiliser sacks, timing mechanisms) that could be associated with the manufacture of an explosive device were found (Fig. 30.1a). Also recovered was a spade, with mud/soil adhered to various parts (Fig. 30.1b). The three were arrested for a range of other offences not connected to this case study. A police intelligence operation concentrated on CCTV footage throughout the border counties of Ireland, where the vehicle was observed a number of times, confusing the picture of where they may have been digging with the spade (if at all). The spade was submitted to the authors; the mud/soil was removed and subjected to geochemical assay assessment by portable XRF (PXRF; see Bergslien *et al.*, 2008 for background on

Figure 30.1. (a) Suspected command wire seized from the suspects' vehicle. (b) Soil/mud-encrusted spade that was used for PXRF analysis. (c) Trench in County Derry–Londonderry where the mortar tube was located. (d) The trench that contained the two mortar rounds.

this method in forensics), using an Oxford Instruments X-MET7000 Series Analyser, calibrated to major element standards.

The results (Table 30.1) show typical soil values for many elements but with elevated potassium (K), chromium (Cr) and titanium (Ti). We have selected these elements as examples only; in the complete work, a canonical or hierarchical cluster analysis would be used as a discriminatory test, and this would be compared to other proxies (e.g. pollen, grain size, soil biomarkers). These results were inconsistent with typical Tellus survey soil values from the border area of Ireland, where the arrest of the three suspects was made. Consequently, it was suggested to police that they extend their scrutiny of CCTV records to encompass areas where larger concentrations of K, Cr and Ti may be observed, including further north in Northern Ireland and some locations in the western border counties of Ireland. As a result, the suspect vehicle was identified at a petrol station on the main A6 road near Magherafelt in south County Derry–Londonderry, near a location where a vehicle fire had been reported by a farmer in the previous days. A search of the area near the fire revealed dug ground (Fig. 30.1c, 30.1d), containing a tube-type mortar in one excavation and mortar rounds in an associated pit. PXRF was deployed on dried samples from this area (Table 30.2), and showed concentrations of elements comparable to those obtained from the spade.

Table 30.1. Portable XRF analysis of the mud/soil adhered to the spade seized from suspects at a location where such K, Ti and Cr contents are uncommon, unlike where the mortar hide was discovered

SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	Na_2O	K_2O	MnO	P_2O_5	Cr_2O_3	Cl	Other	Total
36.1	16.4	14.4	4.4	0.2	6.3	4.1	9.45	0.5	<0.5	0.75	2	4	98.6

Table 30.2. QemScan analyses for the spade and mortar hide locations, for comparison with PXRF

SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	Na_2O	K_2O	MnO	P_2O_5	Cr_2O_3	Cl	Other	Total
33.2	17.1	17.8	5.4	0.4	7	4.5	8.41	0.6	<0.4	0.7	0	3	97.4

To verify the PXRF work, samples were also submitted for QemScan analysis (automated, quantitative scanning electron microscope analysis; see Gottlieb *et al.*, 2000). QemScan measures elements by energy dispersive X-ray of individual particles, whereas PXRF measures element amounts by irradiating the entire exposed sample, so a direct comparison cannot be made, but relative abundances can be considered. Should QemScan, PXRF and the Tellus geochemistry all show a range of elevated and depleted elements, such samples may be compared by further analysis. The results in this case (Table 30.3) show that the PXRF work for provenancing by abundance (but not absolute values) is confirmed by the QemScan method.

While the spade/trench samples compare well, they were significantly different in absolute values from the Tellus results. This is likely because the sample collection and preparation methods are different and further demonstrates that direct comparison is not appropriate. However the Tellus data maps serve to show that areas with low K, Cr and Ti can be excluded from possible origins of the spade/trench soil. Should the different methods display very different geochemical profiles, these may be excluded from the comparison. These data could not be considered as 'associative evidence' (e.g. for use by the court to establish where a suspect had been), as they are not comparable in origin and geochemistry.

Variation: can Tellus data be used as a proxy for control samples?

A more common scenario in the use of soil or sediment in geoforensics is establishing if there is any connection between the soil found on a suspect (shoes, clothing, vehicles) and that at the scene of crime. The sampling and analysis is straightforward if completed close to the time of the event, with standard protocols and preferably using a multiproxy

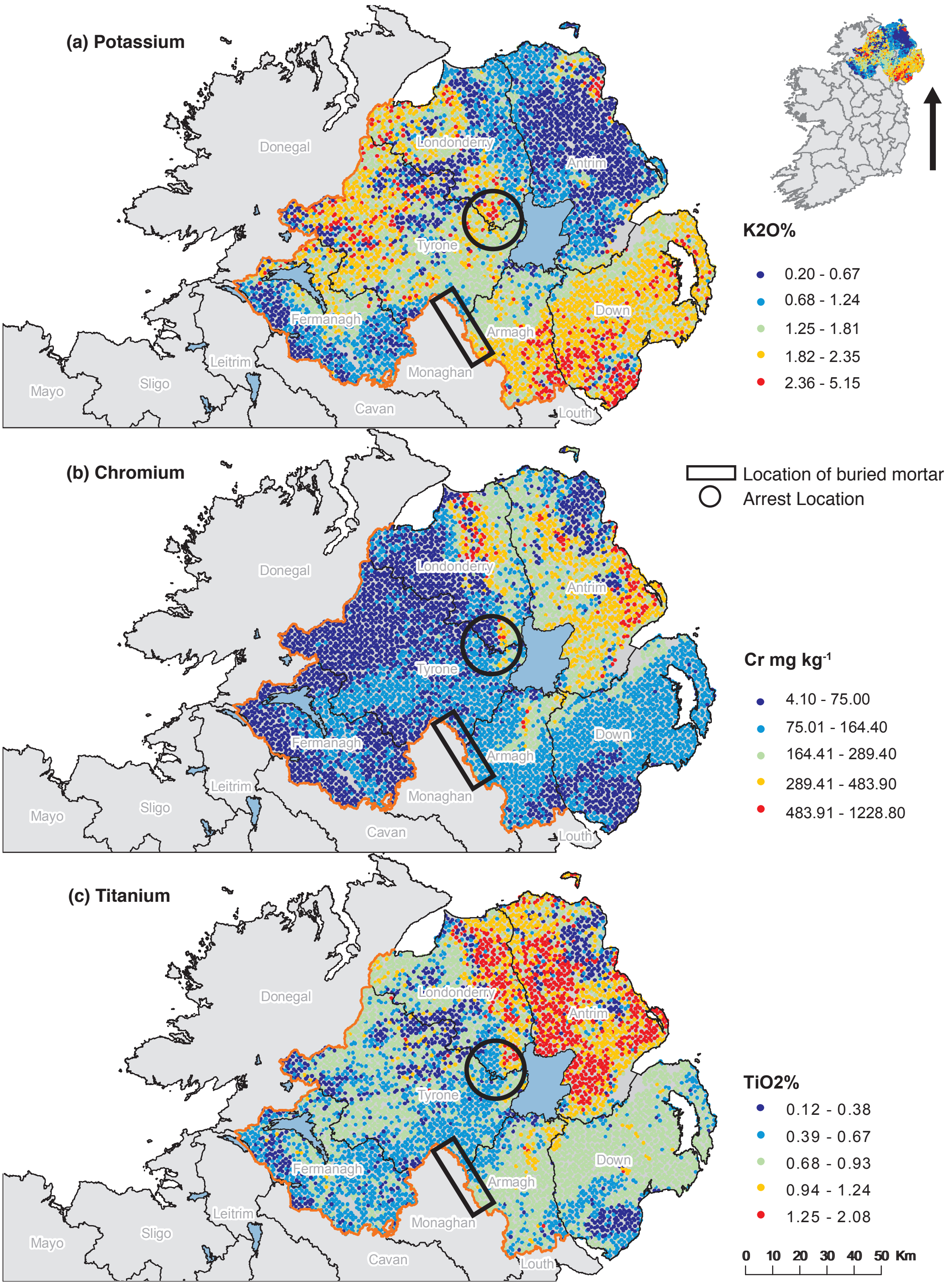
Table 30.3. QemScan analysis of the soil/mud from the mortar tube trench (see Fig. 30.1c).

Sample name	Spade	Mortar tube trench	Mortar rounds trench
Quartz	24.32	24.29	19.40
Plagioclase	19.24	19.80	18.41
Orthoclase	6.56	6.25	6.43
Muscovite	4.42	4.40	5.29
Biotite	4.05	3.84	4.11
Kaolinite	3.66	4.30	6.50
Fe Ca Al silicates	8.05	8.05	8.04
Fe Al silicates	12.68	14.02	13.16
Ca Al Mg silicate	0.11	0.20	0.10
Calcite	0.12	0.08	0.08
Ti phases	4.26	4.31	5.29
Ilmenite	0.22	0.01	0.01
Fe–Ox/CO_3	0.39	0.34	0.85
Pyrite	0.00	0.01	0.01
Apatite	0.02	0.03	0.03
Zircon	0.03	0.02	0.05
Mn phases	0.05	0.04	0.04
Others	0.72	0.61	0.5

methodology (Rawlins *et al*., 2006). We thus have suspect and scene samples, and it is usual to establish what alibi locations and samples may be available such that if the suspect materials originated from an innocent source, unconnected with the crime, they may be used to exonerate the innocent, or not to establish any connection.

In the case of historical enquiries, however, alibi locations may be unknown, compromised or destroyed. Nonetheless, a court of law may still wish to compare suspect and scene samples that are similar by asking, 'what is the possibility of such a sample occurring at some other location where the suspect may have contacted such soil in innocent circumstances?' A database such as Tellus may help inform an answer to such a question, as a range of spatial variation in soil element content from one, through a few, to the full range of 55 elements may be used, as outlined below. In the simplest form, say the suspect

Figure 30.2. Soil geochemistry and location of where the suspects were arrested and where the mortar tube and rounds were located. Geochemistry from the Tellus survey: (a) potassium; (b) chromium; (c) titanium.


(a) Potassium
Donegal
Londonderry
Antrim
Tyrone
Fermanagh
Down
Armagh
Leitrim
Monaghan
Sligo
Mayo
Cavan
Louth
K2O%
0.20 - 0.67
0.68 - 1.24
1.25 - 1.81
1.82 - 2.35
2.36 - 5.15
(b) Chromium
Location of buried mortar
Arrest Location
Cr mg kg-1
4.10 - 75.00
75.01 - 164.40
164.41 - 289.40
289.41 - 483.90
483.91 - 1228.80
(c) Titanium
TiO2%
0.12 - 0.38
0.39 - 0.67
0.68 - 0.93
0.94 - 1.24
1.25 - 2.08
0 10 20 30 40 50 Km

and scene samples both show elevated uranium (U) concentrations, limiting their origins to places in Northern Ireland where U-bearing soils may be found. Consider the full range of elements obtained from the suspect, scene and Tellus data, and a geochemical combination may be obtained by multivariate statistics, such as canonical analysis, that limits the number of possible origins of the samples.

This does not, however, directly answer the question posed in the courtroom of the possibility that another soil could occur, with comparable characteristics, at a location not connected to the crime. Compositional data (closed or constraint data such as percentages or parts per million) are routinely used in courts to express the results of chemical or modal analyses of trace evidence as proportions. The question asked is whether this comparison of percentages and other constraint or closed data is both valid statistically and appropriate for use in a court of law. The Bayesian statistical approach to weighing forensic evidence based on the likelihood ratio calculated on a ranking scheme of the strength of evidence (Aiken, 2008) has been a source of contention in forensics due to the choice of prior knowledge and lack of appropriate reference materials. However, the Tellus data can be used to provide either a statistical likelihood of the range of locations that share common geochemical characteristics or qualitative information on whether the accused may have visited locations with such a soil geochemistry. Our provenance case study (above) is a good example: the suspect material (on the spade) showed a combination of K, Cr and Ti contents that compared (albeit with different units used) to the soil geochemistry of south County Derry–Londonderry (Fig. 30.2), where the mortar was buried. The underlying issue is considered by Lark and Rawlins (2008) and McKinley (2013), and is one of a spatial scale that is smaller than observed in the Tellus database (km). The question is this (again, taken from an actual courtroom event): 'the suspect material may indeed only compare at the regional or km scale to the alleged scene, but what if some small area exists within a larger one, yet with similar make-up to the suspect material?' In this scenario, reference to the Tellus database will not answer the question, as the multiproxy analytical approach must be deployed to decrease the possibility of a chance occurrence of such a soil on a suspect, at a scene of crime, but also in an innocent location.

Conclusions

Baseline, spatially referenced data on soil and sediment properties such as the Tellus and Tellus Border soil and stream sediment geochemical maps provide invaluable intelligence when used to determine the provenance of a displaced sample. Such material may be adhered to a suspect's footwear, clothing, vehicle, weapon, contraband, or in the case study, a spade used to allegedly excavate an area for the concealment of weapons. The Tellus data may also provide general information on variation in soils, but the wide difference in scale and resolution between the Tellus sampling and the typically more focused scene of crime limits the applicability of the data.

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