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An experimental study addressing the use of geoforensic analysis for the exploitation of improvised explosive devices (IEDs)

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ABSTRACT

The use of geoforensic analysis in criminal investigations is continuing to develop, with the diversification of analytical techniques, many of which are semi-automated, facilitating prompt analysis of large sample sets at a relatively low cost. Whilst micro-scale geoforensic analysis has been shown to assist criminal investigations including homicide (Concheri et al., 2011 [1]), wildlife crime (Morgan et al., 2006 [2]), illicit drug distribution (Stanley, 1992 [3]), and burglary (Mildenhall, 2006 [4]), its application to the pressing international security threat posed by Improvised Explosive Devices (IEDs) is yet to be considered. This experimental study simulated an IED supply chain from the sourcing of raw materials through to device emplacement. Mineralogy, quartz grain surface texture analysis (QGSTA) and particle size analysis (PSA) were used to assess whether environmental materials were transferred and subsequently persisted on the different components of three pressure plate IEDs. The research also addressed whether these samples were comprised of material from single or multiple geographical provenances that represented supply chain activity nodes. The simulation demonstrated that material derived from multiple activity nodes, was transferred and persisted on device components. The results from the mineralogy and QGSTA illustrated the value these techniques offer for the analysis of mixed provenance samples. The results from the PSA, which produces a bulk signature of the sample, failed to distinguish multiple provenances. The study also considered how the environmental material recovered could be used to generate information regarding the geographical locations the device had been in contact with, in an intelligence style investigation, and demonstrated that geoforensic analysis has the potential to be of value to international counter-IED efforts. It is a tool that may be used to prevent the distribution of large quantities of devices, by aiding the identification of the geographical location of key activity nodes.

1. Introduction

Geoforensic analysis is the application of techniques and principles derived from the geoscience disciplines to criminal investigations, for both intelligence and prosecution purposes [1–6]. Today, geoforensic analysis is rapidly evolving, with advances made in analytical equipment, facilitating a diversification in techniques, such that analysis is no longer limited to approximations of colour, grain-size and mineralogy [7,8]. Many techniques are now semi-automated, enabling rapid analysis of large sample sets. Advancements in equipment have facilitated improved limits of detection, whilst the development of analytical approaches including Quantitative Evaluation of Minerals by Scanning Electron Microscopy (QEMSCAN) and laser ablation, have enabled sub-particle scale analysis.

1.1. Geoforensic analysis

It has been acknowledged that within the forensic sciences the importance of understanding evidence within a probabilistic framework that relies on an exclusionary approach is critical for effective analysis and interpretation of samples, and subsequent presentation of evidence and/or intelligence [9]. This is in clear contrast to the approach typically adopted within the traditional environmental sciences [10–12]. The adoption of an exclusionary approach (in contrast to association or matching), reduces the

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potential for both false associations and exclusions between samples, which may result in inaccurate interpretations [9].

Experimental studies have begun to consider the effects of pre-, syn- and post-forensic event material transfer, that creates the potential for mixing of environmental and anthropogenic materials derived from different provenances on a single exhibit [8,13–15]. Arguably there is potential for all exhibits in a forensic investigation such as vehicles, footwear, clothing, to preserve mixed source samples. Multiple source transfer adds a level of complexity to an investigation, as failure to distinguish multiple sources may result in the false exclusion of a sample or area of interest. However in harnessing the potential of such occurrences, there exists the opportunity to recreate the geographical journey of an object and/or person. The key to achieving this type of reconstruction is establishing the evidence dynamics of relevant trace materials on the object/person in question, and the utilization of appropriate analytical techniques, which enable individual provenances to be distinguished from one another. There is therefore, a need for simulation studies which investigate pre-, syn- and post forensic event material transfer and persistence in order to develop an evidence based interpretation approach that considers the presence of mixed provenance signals. Where the existence of such mixed provenance samples is possible, it has been argued that there is benefit in utilising analytical approaches that do not homogenise the sample prior to analysis, such as mineralogy by binocular microscopy [16]. It is also necessary to employ independent forms of analysis, so that if there are corroborative findings on a series of samples, the significance of a finding can be articulated clearly whether as evidence for a court of law, or as intelligence for investigators [9,16].

1.2. Security challenge: IED distribution

IEDs pose a considerable security threat on an international scale, in both zones of conflict and peace. Such devices have long been the weapon of choice for a continuum of individuals and groups including terrorists and organised crime groups, in an endeavour to cause harm to people, physical infrastructure, political relations, and economies, as well as a method of protecting goods caches. Improvisation facilitates construction of devices from everyday (non illicit or contraband) items, which are easily purchased and distributed internationally [17], owing to the absence of government exporting licences [18]. The nature of these materials also limits the ability to attribute their source. Moreover, they can be manufactured relatively cheaply, whilst still possessing the potential to produce significant negative impacts [19]. IEDs are expected to be the weapon of choice for the foreseeable future [20,21], with the developing threat of Chemical Biological Radiological and Nuclear (CBRN) IEDs [22,23], and advancements in technology facilitating new methods of device deployment, such as IEDs attached to drones [24].

IEDs are distributed along supply chains consisting of key activities, including raw material sourcing, and device construction, storage and emplacement [25]. These key activities occur at one or more geographical locations/sites (including indoor and outdoor locations), such that there is potential for multiple sources of material to be transferred onto devices [26]. The supply chain is facilitated by a network of individuals including but not limited to, financiers, legitimate raw materials businesses, material/equipment procurers, technical experts, device manufacturers, and those responsible for emplacing devices [27].

Counter-IED (C-IED) is concerned with developing methods to reduce and eradicate the IED threat on an international scale. Techniques, approaches and technologies which make up C-IED are in part informed by device exploitation. Device exploitation refers to the process of obtaining and examining information recovered from IEDs, such as biometric data [28], to derive intelligence to assist the three lines of operation; defeat the device, prepare the force and attack the network [29]. Currently, the use of environmental materials adhering to devices, to derive intelligence as to the geographical location of activity nodes in IED supply chains, has yet to be explored.

Table 1
The supply chain simulated within this study. Details of the underlying bedrock geology and land-use are given. Contains British Geological Survey materials© NERC [2017] [31].

Stage	Supply chain activity nodes	Land-use	Underlying bedrock geology & superficial deposits
1	Raw materials purchased	Urban/city environment. Shops/suppliers used to purchase raw materials: Asda, Maplin, Amazon, Homebase	Not applicable – raw materials in sealed packaging
2	Raw materials transported to storage facility via train and car	Train carriage and car boot	Not applicable
3	Raw materials stored	Housing estate/urban environment. The raw materials used in the construction of the three devices were stored on the ground in an outside storage area, which comprised a disused brick barbeque and tarpaulin roof	Bedrock geology: Close/on the boundary between the Harwich Formation and the London clay Formation Superficial deposits: Kempton Park Gravel Formation
4	Raw materials transported from the raw material storage facility to the build site in the boot of a car	Car boot	Not applicable
5	3 mock devices constructed (constructed on 2 different days, devices 1 on day 1 and devices 2 and 3 on day 2)	Equine pastureland/field	Bedrock geology: Seaford Chalk Formation and Newhaven Chalk Formation Superficial deposits: Head deposits and the Lynch Hill Gravel Member
6	Complete mock devices transported to IED cache on foot	Transported across car park on foot	Not applicable
7	Complete mock IEDs stored approximately 35 m from the construction location	Industrial barn/equine riding arena	Same site as build site, however in an indoor equestrian riding arena, comprising un-consolidated sands and multi-coloured fibrous bundles, set upon a concrete foundation
8	Complete mock devices transported to IED emplacement location in the boot of a car	Car boot	Not applicable
9	Emplacement of mock devices Mock devices covered with vegetation and leaf litter for concealment purposes	Un-landscaped garden bordering small wooded area	Bedrock geology: Close to/on the boundary between the Lewes Nodular Chalk Formation, and the Seaford Chalk and Newhaven Chalk Formations Superficial deposits: Clay-with-flints Formation

The purpose of this study was to establish whether environmental materials i.e. soils and sediments (including anthropogenic additions), were transferred and persisted on device components, from multiple locations i.e. activity nodes, of a simulated IED supply chain. Preferential transfer and decay was considered and contextual information regarding the amount of material recoverable, and the effects of sampling from different components of an IED, established. The study also sought to consider how the information generated by analysing recovered environmental samples could be used to reconstruct the geographical locations where the device had been, in a seek and find investigation, where no control sample is available.

2. Materials and methods

2.1. Supply chain simulation

An IED supply chain was simulated starting from the sourcing of raw materials through to device emplacement, after which mock devices were recovered for exploitation (Table 1). The IED perpetration core model [25] was used in combination with extensive consultation with security professionals from the National Bomb Data Centre & Explosive Ordnance Disposal to develop a simulation of an IED supply chain comprising outdoor and indoor locations (see Table 1) that modelled reality as closely as possible. Owing to the improvised nature of IEDs, those classified as the same type of device, can be very different in dimensions and form, such that modelling device type would not generate a generalisable evidence base for interpretation. For this reason, the study focused on incorporating some of the most commonly used materials i.e. wood, metal, plastic and tape into a wooden pressure plate, victim operated IED, one of the most commonly used devices in the 2001–2014 Afghanistan conflict [30]. In order to assess result consistency, the production and distribution of three identical mock devices was modelled from raw material sourcing to emplacement.

As the study sought to assess primarily whether environmental and anthropogenic materials from multiple activity nodes of a simulated IED supply chain were transferred and subsequently persisted on device components, locations with different bedrock materials were selected, as this is recognised as a factor which in part controls the mineralogical composition of top soil/sediment deposits [32]. The different types of land-use included within the supply chain simulation, endeavours to reflect the types of environments identified in case work examples. Control samples were collected at the supply chain activity nodes for exclusion purposes, however it was not possible to collect control samples from the material source locations as they were retail outlets. An overview map of the locations is provided in Fig. 1.

2.2. Sample preparation

Material was sampled from 8 different areas on the three mock devices as shown in Fig. 2, to assess whether the materials preserved were consistent not only between devices, but between different areas of individual devices. Samples were weighed

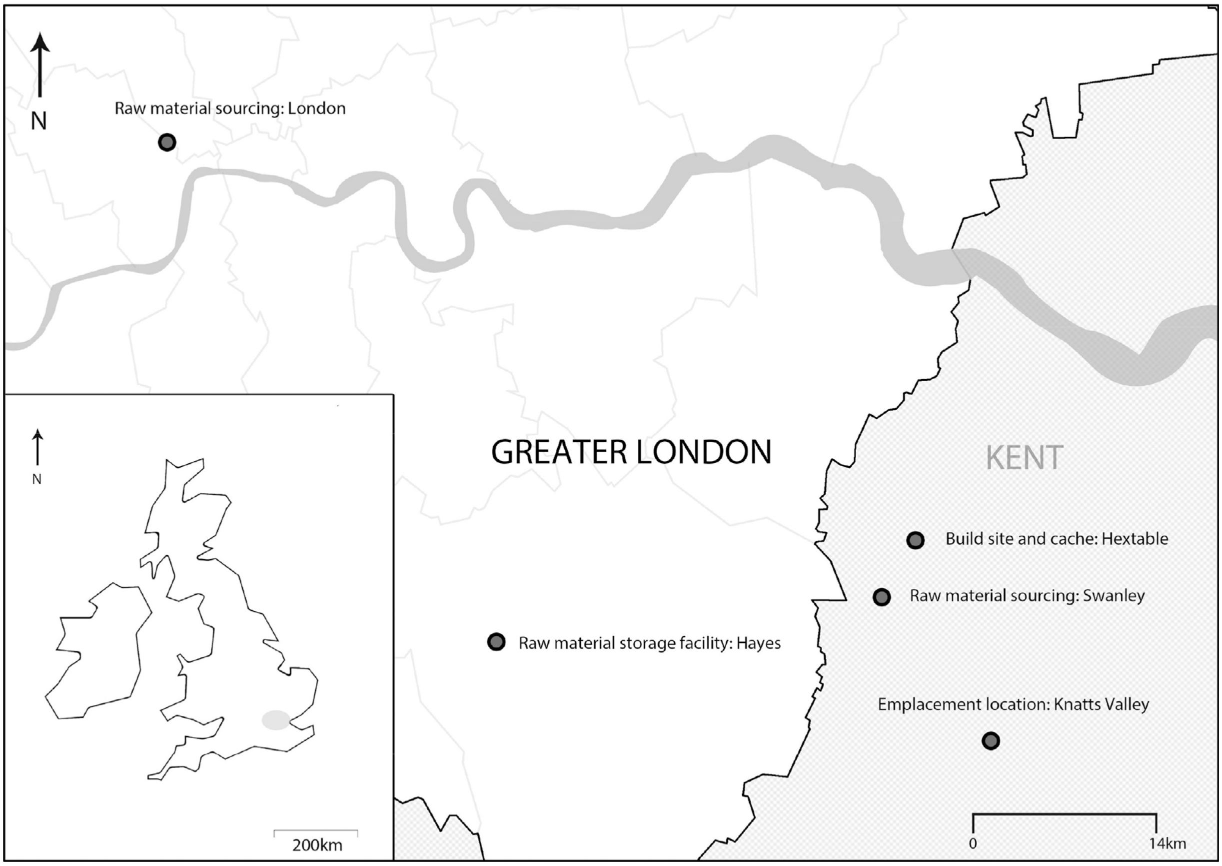


Fig. 1. Map detailing the locations of activity nodes within the simulated IED supply chain. Source location of Amazon plastic containers unknown. Build site and cache at same location, but on different parts of the site.

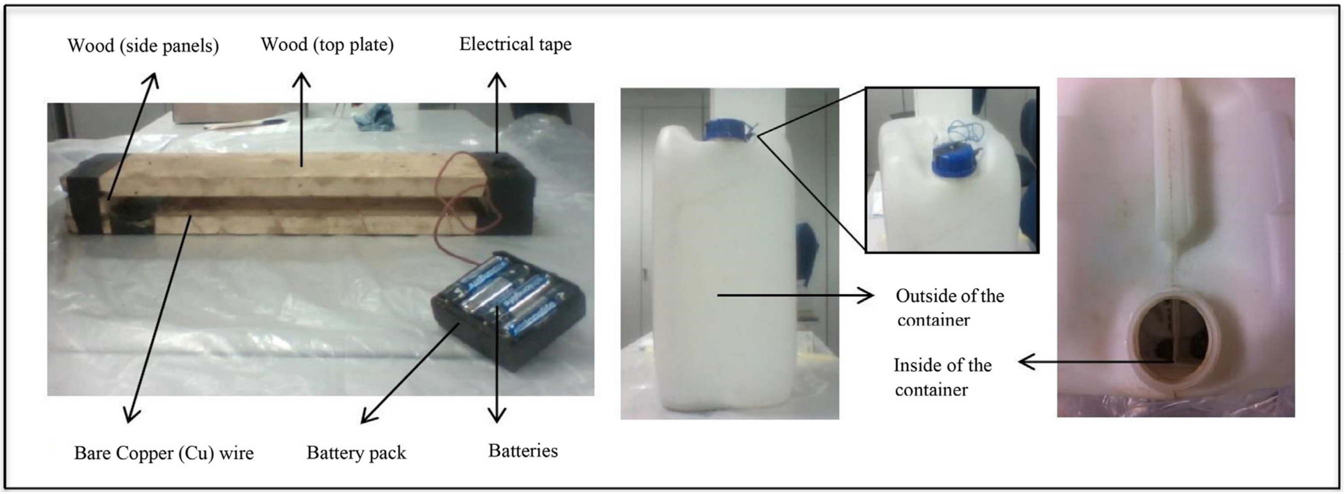


Fig. 2. Sampling locations on all 3 mock devices.

immediately following removal from device components to establish the amount of material recoverable. The material recovered was then compared against control samples taken from the activity nodes. Scanning Electron Microscopy [33–35], binocular microscopy [36–38] and particle size analysis [39–41] were selected as frequently utilised analytical approaches for trace environmental samples in forensic enquiry.

A Low powered Leica S6E L2 binocular microscope was used to identify mineralogy and other materials both in the control samples, and samples recovered from device components. Samples were placed in a petri dish and examined at varying magnifications between 0.63 and 4.0.

Quartz grains recovered from device components were analysed using a Cambridge Stereoscan 90 Scanning Electron Microscope (SEM). From each sample, 50 quartz grains were sampled and mounted on SEM stubs using an adhesive carbon film. Quartz grains were categorised following the method outlined in Bull and Morgan [34].

A Malvern laser granulometer (a Hydro 2000 MU dispersion unit coupled to Mastersizer 2000 laser), which measures particles from 0.02 μm up to 2000 μm, was used to establish the particle size of control samples, and those removed from the three devices. Samples were washed in de-ionized water to remove organic debris, and then mixed using the dispersion unit, to prevent vertical density layering and facilitate separation of remaining aggregates. The sample was automatically measured three times on a single run to assess reproducibility. Gradistat [42] was used to generate particle size descriptions and histograms were produced using excel.

Table 2
Amount of material (g) recovered from the eight different sampling locations on the three complete mock devices.

Sample location	Device 1	Device 2	Device 3
Batteries	0.3044	0.1366	0.0699
Battery pack	0.7326	0.0874	0.0857
Bare copper wire	None	0.1133	0.1029
Electrical tape	Trace	Trace	Trace
Outside of container	0.2476	0.2694	0.4564
Inside of container	Variable	Variable	Variable
Wood (side panels)	0.0717	0.181	0.2759
Wood (top plate)	3.6231	2.7541	2.6747

3. Results

3.1. Recoverable sample weights

There was variability in the preservation of material on/in the mock IEDs derived from one or more activity nodes of the simulated IED supply chain (Table 2). For all three mock devices, the largest amount of material persisted on the wood (top plate), whilst the smallest amount of material recovered varied between the three mock devices. The only sampling location that appeared to preserve no material was the bare Cu wire of mock device 1. It was not possible to weigh the material preserved on the electrical tape, as it could not be effectively recovered from the adhesive, without potentially crushing/modifying certain grains in the sample. Moreover, it was not possible to recover all of the material preserved on the device components, as some of the material was inaccessible (for example, lodged in the lattice of the wood), such that the total weight represents the material that was recoverable rather than the total amount preserved. In total, the greatest amount of material was recovered from mock device 1. At the IED build site, stones were purposefully added to the inside of the container, as they are commonly used in IEDs to increase fragmentation during a blast. For this reason, the weight of the material recovered from the inside of container is listed as 'variable' in Table 2, as it is dependent on the amount added by the device manufacturer.

3.2. Mineralogy

3.2.1. Control samples

Low powered binocular microscopy revealed that all control samples, with the exception of the car boot, contained quartz (clear, milk and citrine), with some grains demonstrating black mineral inclusions as Table 3 denotes. In addition, control samples from the raw material storage facility (RMSF) contained individual particles of mica, charcoal, paint flakes, organic debris and aggregates of quartz (both with and without inclusions) mica, charcoal and organic debris termed A2. Individual grains of calcite, stones/clasts (chalk, flint and tarmac), animal hair and aggregates of quartz (both with and without inclusions), calcite, tarmac and organic debris termed A1, were identified exclusively in the build site control samples. In the control samples taken from the IED cache, prasiolite and multi-coloured fibres (individual and bundle

Table 3

Minerals and other materials present in the 4 control samples, and samples recovered from components of the 3 complete mock devices. No material recovered (N).

Device number/location	Sample name	Quartz (clear/citrine/ milk)	Prasiolite	Mica	Calcite	A1: Aggregate of quartz, calcite, tarmac and organic debris	A2: Aggregate containing quartz, mica, charcoal and organic debris	Clasts (chalk, flint, tarmac)
Raw material storage facility	Control sample	✓	x	✓	x	x	✓	x
Car boot	Control sample	x	x	x	x	x	x	x
Build site	Control sample	✓	x	x	✓	✓	x	✓
IED cache	Control sample	✓	✓	x	x	x	x	x
Emplacement	Control sample	✓	x	x	x	x	x	x
Spare components sampled prior to transport to the build site	Wood (side panels)	✓	x	✓	x	x	✓	x
	Wood (top plate)	✓	x	✓	x	x	✓	x
	Plastic coated wire	✓	x	x	x	x	✓	x
	Batteries	✓	x	✓	x	x	✓	x
	Battery pack	✓	x	✓	x	x	✓	x
Spare components sampled following construction at the build site	Wood (side panels)	✓	x	x	✓	✓	x	x
	Wood (top plate)	✓	x	x	✓	✓	x	x
	Plastic coated wire	✓	x	x	x	✓	x	x
	Batteries	✓	x	x	✓	✓	x	x
	Battery pack	✓	x	x	✓	✓	x	x

Device number/location	Sample name	Tarmac	Charcoal	Brick	Organic material	Plant material	Multi-coloured fibres	Paint flake	Animal hair	Insect shell	Black fibres	Transparent spheres
Raw material storage facility	Control sample	x	✓	✓	✓	✓	x	✓	x	✓	x	x
Car boot	Control sample	x	x	x	x	x	x	x	x	x	✓	x
Build site	Control sample	✓	x	✓	✓	✓	x	x	✓	✓	x	✓
IED cache	Control sample	✓	x	x	x	x	✓	x	x	x	x	✓
Emplacement	Control sample	x	x	✓	✓	✓	x	x	x	✓	x	x
Spare components sampled prior to transport to the build site	Wood (side panels)	x	✓	x	✓	x	x	x	x	x	x	x
	Wood (top plate)	x	✓	✓	✓	✓	x	x	x	✓	x	x
	Plastic coated wire	x	✓	x	✓	x	x	x	x	x	x	x
	Batteries	x	✓	x	✓	x	x	x	x	x	x	x
	Battery pack	x	✓	✓	✓	✓	x	x	x	✓	x	x
Spare components sampled following construction at the build site	Wood (side panels)	✓	x	x	✓	✓	x	x	x	x	x	x
	Wood (top plate)	✓	x	x	✓	✓	x	x	x	x	x	x
	Plastic coated wire	✓	x	x	✓	✓	x	x	x	x	x	x
	Batteries	✓	x	x	✓	✓	x	x	x	x	x	x
	Battery pack	✓	x	x	✓	✓	x	x	✓	x	x	✓

form) were identified. Transparent spheres, were identified in the control samples taken from both the build site and cache. Such spheres are typically observed in road paint [43], and/or represent fly ash particles [44]. The emplacement location possessed no identifiable material exclusive to that site. The only materials recoverable from the boot of the car were black fibres.

3.2.2. Device samples

The environmental materials recovered from different device components are presented in Table 3, in order to provide an assessment of the variability between the three mock devices that were constructed in the same manner. The occurrence of individual grains of quartz (clear, milk and citrine) both with and without inclusions, calcite, tarmac, organic material and A1, were universal across all three mock devices (Table 3), for all eight sampling points, with the exception of the bare copper wire of mock device 1, where no material was recovered. The battery pack of mock device 1 was the only component to contain A2, consistent with the raw material storage facility (RMSF) control sample.

Material from the inside of the containers of all three mock devices, the batteries of mock device 1, and the tape of mock device 2 were the only samples not to display fibres identified in the IED cache control sample (Table 3). The inside of the containers were the only sample locations which comprised stones/clasts of chalk, tarmac and flint, consistent with control samples taken from the IED build site. White and brown animal hair, likewise only in control samples taken from the IED build site, were recovered from the inside of the container of all three mock devices, as well as from the bare copper wire of mock device 3 and the electrical tape of mock device 1.

3.2.3. Spare components

Table 4 presents the environmental materials recovered from spare components before transport to the IED build site, and following mock device construction. Most notably is the presence of A2, and individual grains of charcoal on all spare components analysed prior to movement to the IED build site, and their absence on other spare components following device construction. Individual mica grains were observable on all spare components with the exception of the plastic coated wire before movement to the IED build site. After the construction of the mock devices, no mica grains were identifiable on any of the spare components.

3.3. SEM

3.3.1. Control samples

In total, 6 different grain types were classified during QGSTA, descriptions of these grain types are provided in Table 5. All four control samples contained type 1 and type 2A quartz grains (Table 6). Both the IED build site and the emplacement location control samples comprised type 3A quartz grains. Types 2B and 3B were identified exclusively in the IED build site control sample, whilst grain type 4 was only identified in the IED cache control sample. Many of the quartz grains at both the IED build site and the IED cache, regardless of type, displayed complete grain breakage.

3.3.2. Device samples

Types 1 and 2A quartz grains were recovered from all components of the three mock devices, with the exception of the bare copper wire of mock device 1, where no material was recovered (Table 7). The inside of the container of mock device 1 and the tape of mock device 3 were the only components which displayed type 3B quartz grains. As with the control samples, many of the quartz grains, regardless of type, displayed complete grain breakage.

3.4. Particle size analysis (PSA)

3.4.1. Control samples

Observation of particle size distribution curves and data revealed differences between the four control samples (Fig. 3). Descriptive data generated using GRADISTAT [42], identified the raw material storage facility and the emplacement location as displaying bi-modal distributions, with the former however being very poorly sorted, whilst the latter was poorly sorted. Both the IED build site and the IED cache displayed a uni-modal distribution, however the former was considered very poorly sorted and the latter moderately well sorted. The IED cache demonstrated the narrowest particle size range between 16 μm–710 μm, whilst the emplacement location displayed a range between 2 μm–1100 μm. Both the raw material storage facility and the IED construction site possessed the largest particle size ranges between 1 μm–2000 μm.

3.4.2. Device samples

Particle size data was largely variable for the same component across the three mock devices (Fig. 4). Despite much variability, a number of samples demonstrated particle size distribution patterns which could not be discriminated from one another, including the top wooden panel of mock devices 1 and 3, however such consistency was limited. Interestingly, particle size distribution histograms of material recovered from the inside of containers revealed that mock devices 2 and 3, displayed a similar pattern of variation, different to that of the inside of the container of mock device 1. Particle size distribution curves produced for material recovered from mock device components could largely be discriminated from all 4 control samples.

4. Discussion

Mineralogy and QGSTA results were relatively consistent for individual device components across the mock three devices (Tables 3 and 7). However, particle size distribution data of recovered materials, was far more variable for the same components, across the three devices (Fig. 4).

4.1. Comparative investigative approach

A comparative style approach was used to assess whether environmental materials were transferred and preserved from multiple activity nodes of the simulated IED supply chain. All three independent techniques deployed indicated that the samples recovered from different components of the three devices, recorded a mixed provenance signal. This indicates that material was transferred and preserved from two or more nodes of the IED supply chain, and not just the last activity node visited, i.e. the emplacement location. Where possible, binocular microscopy and SEM results were used to exclude supply chain sites from which recovered environmental materials analysed, were not transferred and/or preserved, while PSA results were used only as descriptors.

Observation of the mineralogical constituents recovered from the three complete devices demonstrated that the battery pack of mock device 1 was the only component to preserve A2, which were only identified in the RMSF control sample. Therefore, with the exception of the battery pack of mock device 1, the mineralogical constituents recovered from the components of the three complete mock devices, exclude the RMSF as an IED node, despite it being one. Although QGST data did not exclude the RMSF as an activity node, the two grain types identified in the control sample i.e. types 1 and 2A (Table 6) from the RMSF, were also identified in control samples taken from the three other locations, such that it is not

Table 4

Minerals and other materials recovered from spare components, both prior to movement of the raw materials to the IED build site, and following construction.

Device number/location	Sample name	Quartz (clear/citrine/milk)	Prasiolite	Mica	Calcite	A1: Aggregate of quartz, calcite, tarmac and organic debris	A2: Aggregate containing quartz, mica, charcoal and organic debris	Clasts (chalk, flint, tarmac)	Tarmac
Raw material storage facility	Control sample	✓	x	✓	x	x	✓	x	x
Car boot	Control sample	x	x	x	x	x	x	x	x
Build site	Control sample	✓	x	x	✓	✓	x	✓	✓
IED cache	Control sample	✓	✓	x	x	x	x	x	✓
Emplacement	Control sample	✓	x	x	x	x	x	x	x
Spare components sampled prior to transport to the build site	Wood (side panels)	✓	x	✓	x	x	✓	x	x
	Wood (top plate)	✓	x	✓	x	x	✓	x	x
	Plastic coated wire	✓	x	x	x	x	✓	x	x
	Batteries	✓	x	✓	x	x	✓	x	x
	Battery pack	✓	x	✓	x	x	✓	x	x
Spare components sampled following construction at the build site	Wood (side panels)	✓	x	x	✓	✓	x	x	✓
	Wood (top plate)	✓	x	x	✓	✓	x	x	✓
	Plastic coated wire	✓	x	x	x	✓	x	x	✓

Device number/location	Sample name	Charcoal	Brick	Organic material	Plant material	Multi-coloured fibres	Paint flake	Animal hair	Insect shell	Black fibres	Transparent spheres
Raw material storage facility	Control sample	✓	✓	✓	✓	x	✓	x	✓	x	x
Car boot	Control sample	x	x	x	x	x	x	x	x	✓	x
Build site	Control sample	x	✓	✓	✓	x	x	✓	✓	x	✓
IED cache	Control sample	x	x	x	x	✓	x	x	x	x	✓
Emplacement	Control sample	x	✓	✓	✓	x	x	x	✓	x	x
Spare components sampled prior to transport to the build site	Wood (side panels)	✓	x	✓	x	x	x	x	x	x	x
	Wood (top plate)	✓	✓	✓	✓	x	x	x	✓	x	x
	Plastic coated wire	✓	x	✓	x	x	x	x	x	x	x
	Batteries	✓	x	✓	x	x	x	x	x	x	x
	Battery pack	✓	✓	✓	✓	x	x	x	✓	x	x
Spare components sampled following construction at the build site	Wood (side panels)	x	x	✓	✓	x	x	x	x	x	x
	Wood (top plate)	x	x	✓	✓	x	x	x	x	x	x
	Plastic coated wire	x	x	✓	✓	x	x	x	x	x	x

Table 5
Description of the different quartz grain types identified in the four control samples, using SEM.

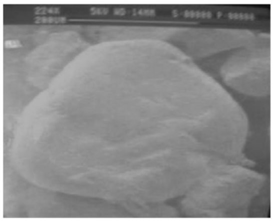
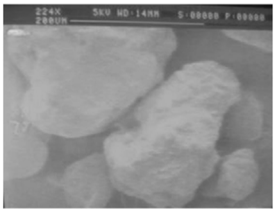
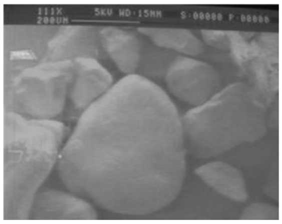
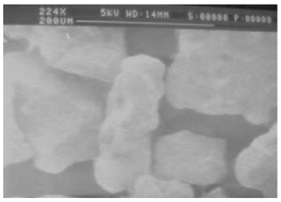
Grain type	Characteristics	Image
Type 1	Sub-angular to sub-rounded smooth grains, no mechanical abrasion on grain edge, old conchoidal fractures, surface of grain shows some diagenetic etch marks	
Type 2A	Angular grains, no mechanical abrasion on grain edge, extensive diagenetic etching	
Type 2B	Angular grains, no mechanical abrasion on grain edge, clean face demonstrating no diagenetic etching	
Type 3A	Rounded to sub-rounded grains, no mechanical abrasion on grain edge, extensive diagenetic etching such that all other surface features are lost	
Type 3B	Rounded to sub-rounded, no mechanical abrasion on grain edge, clean face demonstrating no diagenetic etching	
Type 4	Elongate grains, no mechanical abrasion on grain edge, old conchoidal fractures, surface of grain shows some diagenetic etch marks	

Table 6
The number of quartz grains types identified in each sample. For each sample n = 50.

Control samples	Type 1	Type 2A	Type 2B	Type 3A	Type 3B	Type 4
Raw material storage facility	44	6	0	0	0	0
IED build location	19	22	5	3	1	0
IED cache	39	9	0	0	0	2
IED emplacement location	27	14	0	9	0	0

Table 7
Number of grains of each quartz grain type identified in samples recovered from mock device components. For each sample n = 50. N: no material recovered. It is important to note, counts do not necessarily represent the proportion of different grain types within the sample as a whole.

Device	Location	Type 1	Type 2A	Type 2B	Type 3A	Type 3B	Type 4
1	Wood (side panels)	39	2	5	1	0	3
	Wood (top plate)	43	3	0	0	0	4
	Bare CU wire	N	N	N	N	N	N
	Batteries	35	13	0	2	0	0
	Tape	31	14	5	0	0	0
	Battery pack	20	23	4	2	0	1
	Inside container	26	20	2	1	1	0
	Outside container	39	6	0	2	0	3
2	Wood (side panels)	26	17	4	0	0	3
	Wood (top plate)	28	13	5	0	0	4
	Bare CU wire	15	27	4	1	0	3
	Batteries	16	24	5	0	0	5
	Tape	21	19	6	4	0	0
	Battery pack	22	15	6	2	0	5
	Inside container	24	22	3	1	0	0
	Outside container	15	29	4	2	0	0
3	Wood (side panels)	25	18	1	0	0	6
	Wood (top plate)	36	12	0	2	0	0
	Bare CU wire	19	27	0	4	0	0
	Batteries	22	21	5	1	0	1
	Tape	14	29	4	2	1	0
	Battery pack	29	17	1	2	0	1
	Inside container	22	23	4	1	0	0
	Outside container	12	29	7	2	0	0

possible to determine whether the occurrence of types 1 and 2A, reflects the RMSF, and/or the other 3 locations.

By analysing spare IED components from the RMSF, which were sampled prior to transportation to the IED build site, it was possible to identify that charcoal and A2 were transferred from the RMSF onto spare components (Table 4). However, following the construction of devices at the build site, analysis of spare components (which underwent the device construction process) revealed that such material derived from the RMSF was not preserved. This would suggest that the loss of such material may be a function of movement of the raw materials either to the IED build site or during device construction. Preferential decay of specific materials could influence the inferences made from the analysis results, and lead to the possible false exclusion of supply chain activity nodes.

Paint flakes were only identified in the control sample taken from the RMSF, and in very small quantities i.e. 2 flakes (Table 3). No paint flakes were identified on spare device components which were sampled prior to transport of the raw materials to the IED build site (Table 4), this highlights the issue of a rare component being found at the source, but it not being transferred onto objects and/or people which have been at that location.

A1, individual grains of calcite, animal hair and clasts of flint, chalk and tarmac were identified exclusively in the control samples taken from the IED build site, and thus their occurrence on device components was used as an indicator of this activity node (Table 3). The aggregates were observed on all components of the three devices, whilst the stones/clasts were only identified in the inside of the container of all three devices. Animal hair was noted on the bare copper wire of device 3, the electrical tape of device 1, and the inside of the container of all three devices. The identification of A1, individual grains of calcite, animal hair and clasts of flint, chalk and tarmac, is indicative of material from the IED build site having been transferred and preserved on all three mock devices. Moreover, type 2B grains, which were identified only in the build site control sample, were identified on at least 4 components of all three devices.

Prasiolite, multicoloured fibres and type 4 grains were identified only in the IED cache control sample, and were therefore used as indicators of this activity node (Table 3). Unlike prasiolite where only 2 grains were identified, the multicoloured fibres were extremely common in the control sample. Samples recovered from the inside of the container of all three devices were the only samples not to comprise multicoloured fibres indicative of the IED cache. The absence of multicoloured fibres suggests that the IED cache was not the geographical source of material recovered from the inside of the three containers. The occurrence of the multicoloured fibres (on all other components) and type 4 grains (on at least 3 other components) is indicative of material from the IED cache being transferred and preserved on mock devices.

As discussed it was possible to exclude the cache and RMSF from having contributed to the material recovered from the inside of the 3 containers. Moreover, because the inside of the container was only opened at the build site to add the enhancement and mock explosive, and then resealed, it is probable that the recoverable material preserved was sourced only from the build

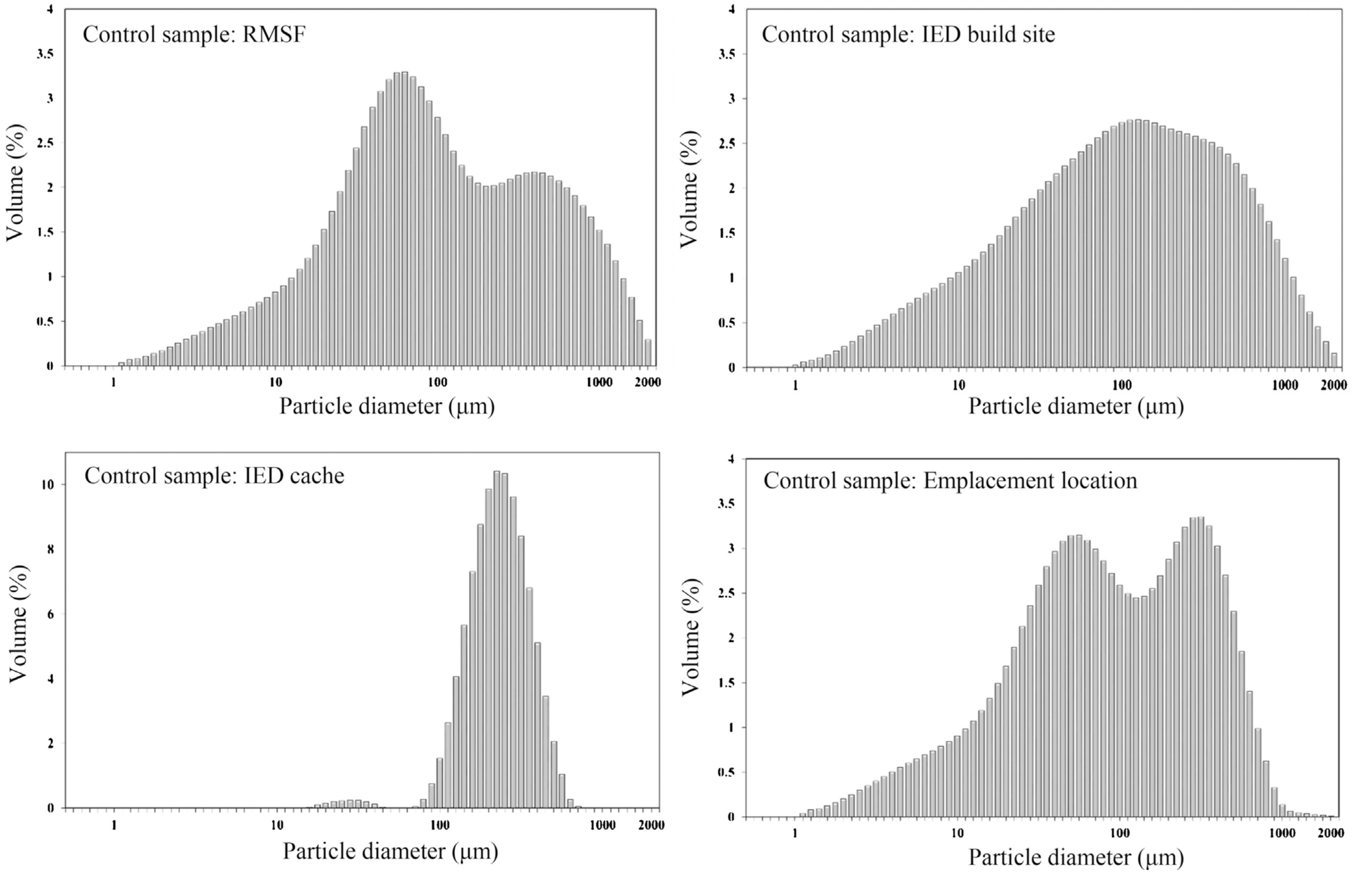


Fig. 3. Particle size distribution histograms of control samples.

site. From this particular example it would seem possible that the inside of the container may preserve a mineralogical and QGST signal representative of a single node i.e. the IED build site, reducing the complexity of mixed provenance sample interpretation. However, this observation is clearly case specific and would depend upon the manner in which the device was constructed; further contextual research would be required to establish whether this is a more generalizable trend.

Unlike control samples taken from the RMSF, IED build site, and IED cache, the emplacement location control sample did not comprise constituents or grain types that distinguished this location from the other activity nodes. It was only the absence of certain constituents, including animal hair, multicoloured fibres, transparent spheres, A1, and A2, and grain types i.e. 2B, 3B and 4 (Table 3 and 7) that could distinguish the emplacement location from the other locations. This adds complexity during interpretation, as it is not possible to determine whether the occurrence of constituents consistent with the emplacement location, were from the emplacement site or another node. Nevertheless, in adopting the exclusion principle, interpretation of the mineralogy and QGSTs of the environmental material recovered from all components of the three mock devices, was such that the emplacement location could not be excluded as having contributed material to all components of three devices, with the exception of the bare Cu wire of device 1, where no material was recovered.

Fibres from the inside of the car (black) were distinguished from IED cache fibres (multicoloured) based on their colour (Table 3). No fibres pertaining to the inside of the car were identified in any of the material recovered from components of the three devices using binocular microscopy.

The preservation of material derived from multiple provenances on a single device highlighted the importance of selecting appropriate analytical techniques that do not produce a bulk environmental signature, as this inhibits the ability to distinguish individual provenances within a mixed source sample. In this case for example, comparison of the grain size distribution of a sample taken from the outside of the container of mock device 3 with the four control samples would have resulted in the exclusion of all four control samples as potential nodes of the IED supply chain (Figs. 3 and 4). Given that PSA produces a bulk signature, PSA was used solely as a descriptive technique in this pilot study. PSA results indicate that the samples are mixed provenance and/or that preferential transfer and decay of particular grain sizes onto mock device components has occurred.

It is important to recognise that all adhering environmental materials may not be recoverable, particularly for certain types of analysis, as was the case for material adhering to the electrical tape, which could be analysed using an SEM and a binocular microscope, but not a laser granulometer. Failure to analyse these materials could affect the inferences that it is possible to make, and must be acknowledged during interpretation and presentation of results.

By adopting a comparative approach, it was possible to illustrate that environmental materials were transferred and preserved from multiple activity nodes of the simulated supply chain, on mock device components (Fig. 4). Identifying that such transfers occur and persist indicates that there is significant potential for the use of geoforensic analysis as a method to reconstruct the geographical journey of an IED through a supply chain. However, this would rely on the use of analytical techniques and an interpretative approach which are capable

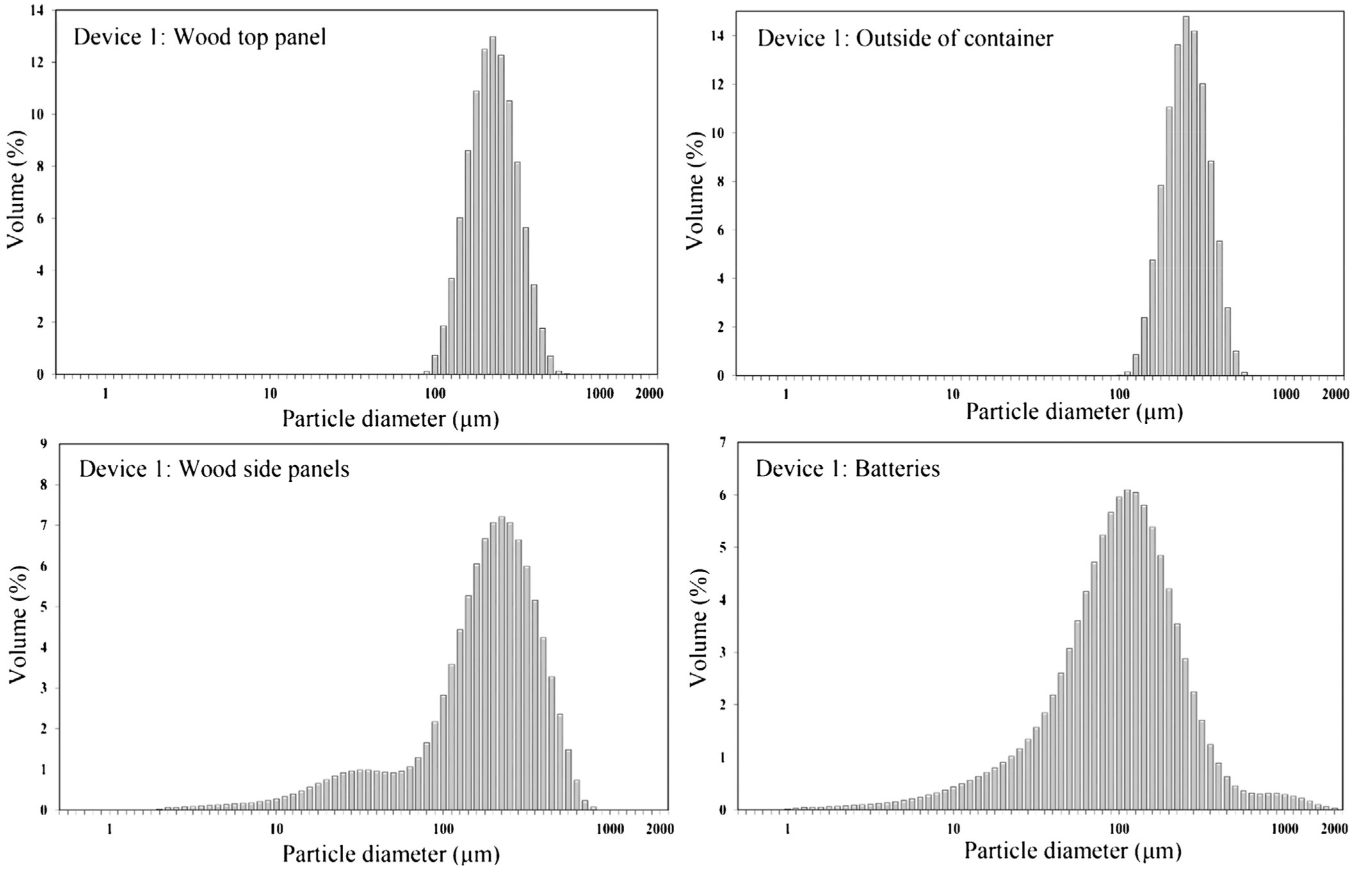


Fig. 4. Particle size distribution histograms of material recovered from different components of the mock three devices.

of distinguishing different geographical sources within a single sample.

4.2. Secondary transfer

Binocular microscopy revealed the presence of tarmac particles and transparent spheres in control samples taken from both the IED build site and cache (Table 3). The transparent spheres identified are commonly found in road paint [43]. Such a finding in a seek and find investigation, in which no comparator samples are available, would suggest one or more nodes of the supply chain to be located on, along, or close by a road side e.g. grass bank, however this was not the case. One possible explanation for such results, is that both the equine pastureland and riding arena have vehicles driving through them, and are also used for overflow parking. Cars entering the two sites may deposit tarmac and transparent spheres from their wheels, previously transferred onto the wheels from roads. Such results demand appreciation of the potential for secondary transfer between different sites, so to limit false positive and negative exclusions of a geographical location during seek and find investigations. Alternatively, the transparent spheres recovered may be directly deposited fly ash particles [44]. Further investigation by chemical analysis may help to ascertain the source of the transparent spheres if there specific provenance was pertinent to the forensic reconstruction.

4.3. Temporal spatial variation in particle size at a single location in the supply chain

As discussed in Section 4.1, through exclusion and using contextual information, it is likely that the RMSF, IED cache and emplacement location can be excluded as having contributed material to the inside of the 3 containers. However the particle size distribution of material recovered from the inside of all three containers does not correspond with the distribution of the control sample taken from the IED build site (Figs. 3 and 4). One potential explanation for this is the presence of small scale spatial variation in particle size distribution at the build site. The material added to the inside of the container to enhance fragmentation, was taken from a location within the field where there were clusters of pebbles. However the control sample for the build site was taken 25 m away, where the mock devices were actually constructed. Alternatively, this variation could be a product of heterogeneity within the sample bags containing the recovered materials and control samples, such that the distribution curves produced are not representative of the whole sample. It is important to remember that comparison using PSA is based on the assumption that a recovered sample will possess material that has both the same grain sizes of the control sample, and also the same distribution. This is unlike the mineralogical and QGSTA approach taken within this study.

Despite consistency in the mineralogy and QGSTs of material recovered from the inside of the containers in all three devices (with the exception of a type 3B grain recovered from device 1), the particle size distribution varied between mock device 1, and mock devices 2 and 3 (Fig. 3). It is possible, given that mock device 1 was built on a different day (dry weather conditions) to devices 2 and 3 (built following wet and strong wind weather conditions), that the observed differences could be attributed to the saturated ground becoming re-worked by equine activity. Alternatively, small-scale particle size variability within the field, and/or sample bag heterogeneity may explain the different particle size distributions.

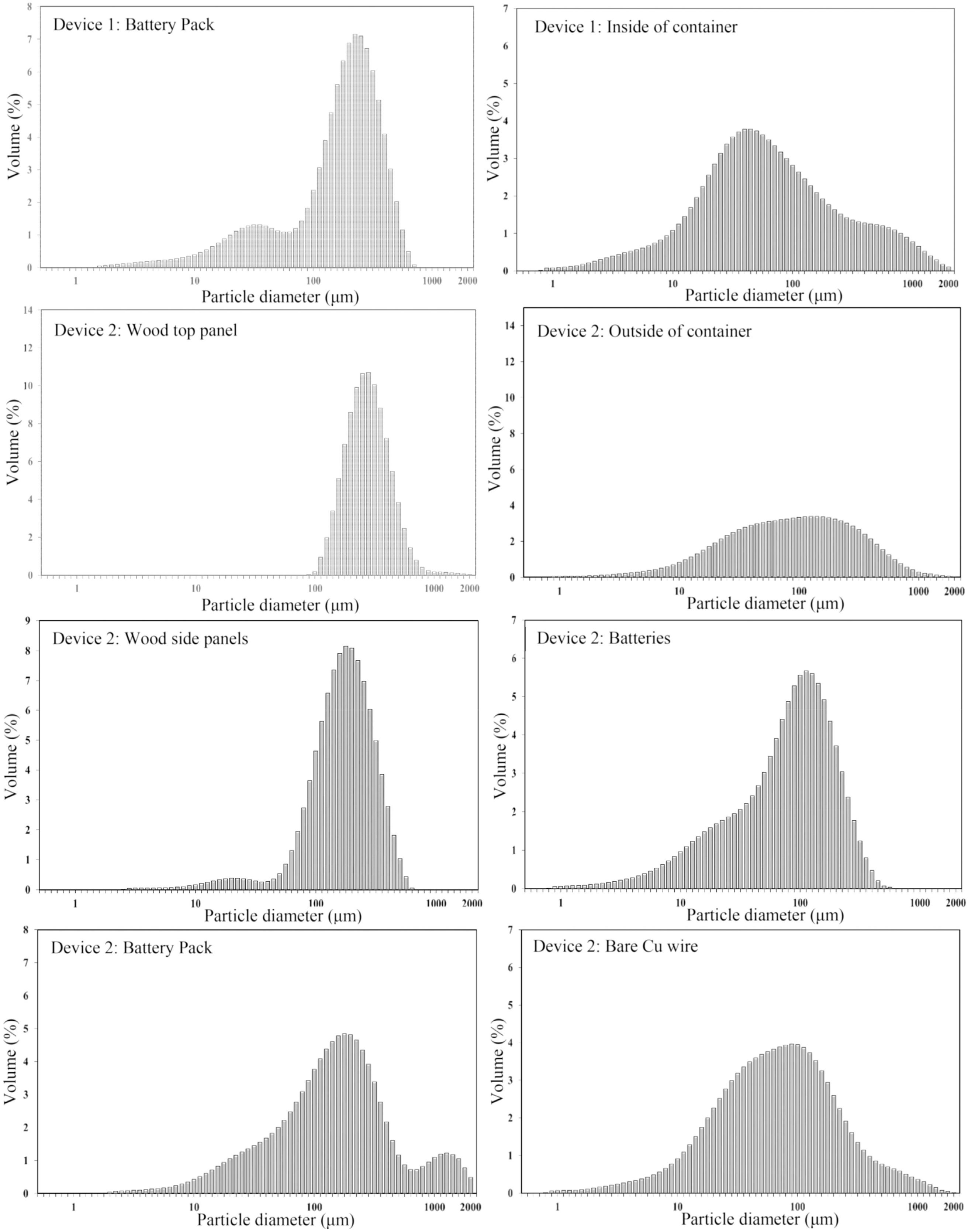


Fig. 4. (Continued)

The significance of these findings is important as it emphasises the need for caution when using particle size analysis in a forensic enquiry, as other studies have demonstrated [45,46]. Such findings combined with the inability of PSA to distinguish individual provenances in a mixed sample, substantiates the case for PSA to be used as a descriptive tool as opposed to an exclusionary

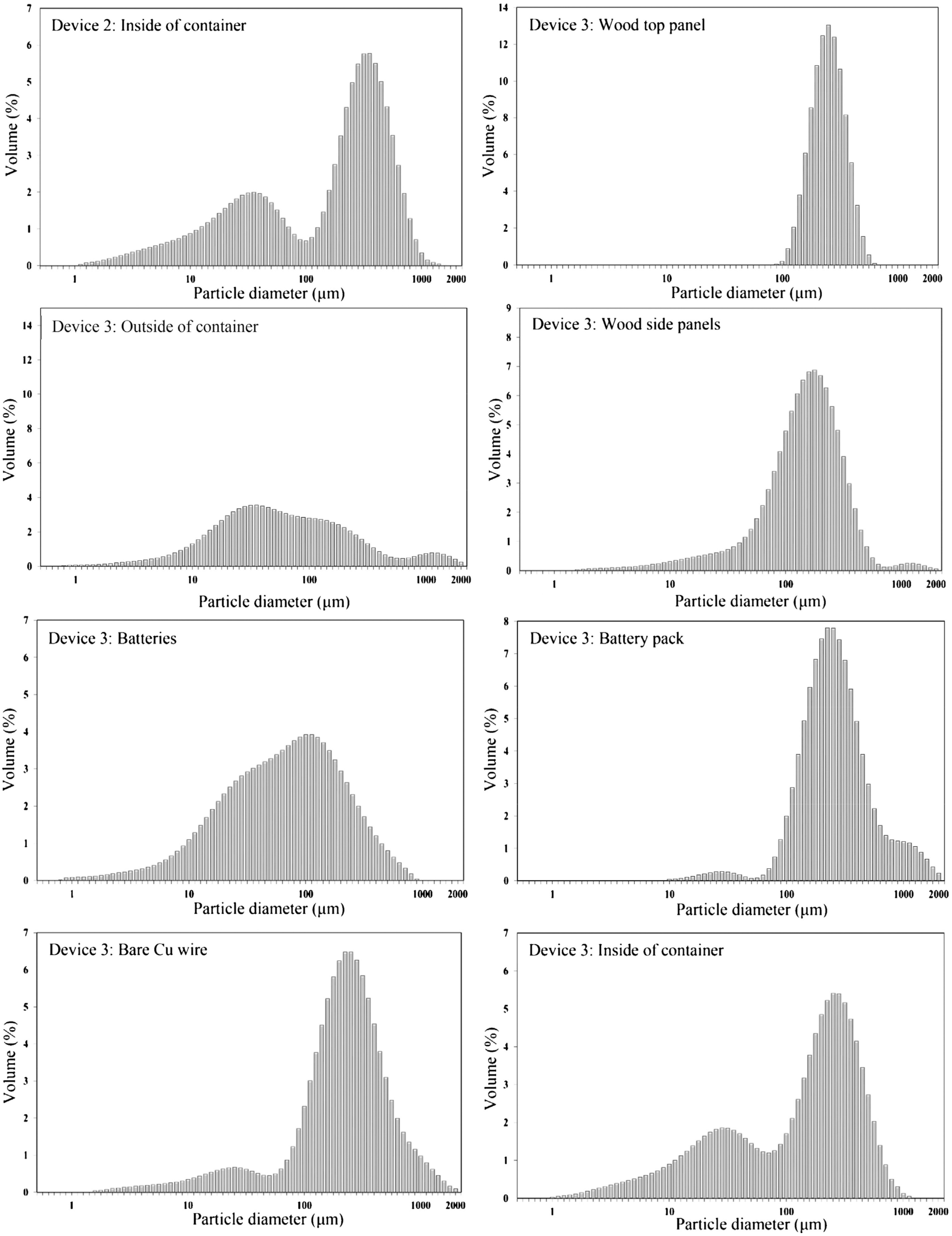


Fig. 4. (Continued)

Table 8
Environments excluded given the absence of common quartz grain surface features [34].

Absent texture	Environmental exclusion
Blocky breakage	Glacial
Glacial grinding and crush marks	Glacial
Grain to grain impact collision features	Turbulent rivers, wave zone of beach, desert
Filaments	Wooded environment with humic soils
Grain edge abrasion	Subaqueous environment
V-shaped pits/indentors	Subaqueous environment
Hertzian/star shaped fractures	Subaqueous environment
Platy textures	Mature aeolian sand seas

technique. Exclusionary interpretations that are made using PSA results should be treated tentatively and in context with the results from other independent forms of analysis.

4.4. Seek and find investigation

Although the main aim of the study was to establish whether environmental materials were transferred and preserved on mock device components from multiple activity nodes of the simulated IED supply chain, consideration was also given to use of the results in a seek and find style investigation. In combining results from both QGSTA and mineralogy, it was possible to exclude a number of environments from having been used in the simulated supply chain. The application of results derived from particle size analysis to the identification of potential geographical provenances was not considered due to the comparative nature of the technique.

The presence of quartz in all samples recovered from device components provided limited information as to the type of environment from which material was derived, owing to its ubiquitous nature. However, QGSTA provided intelligence fundamental for environmental provenance reconstruction. The majority of the quartz grains recovered from different components of the three devices displayed varying degrees of diagenetic alteration, whilst a small number demonstrated complete grain breakage. During pedogenesis, both acids and bases within fluids percolating through soils have the potential to modify the surface of quartz grains by either solution or deposition of precipitates [34]. The orientated etch marks on the surface of the grains recovered from different components of the three mock devices are a likely function of solution, thus their presence is suggestive of a geographical provenance i.e. IED supply chain activity node/s with soil formation. Although the limited features present did little to indicate a specific type of environment from which the samples were derived, the absence of surface textures facilitated the exclusion of a number of different types of environments and bedrock geologies as potential sources of the recovered material. Table 8 details the environments that can be excluded given the absence of a number of common surface features.

Geographically specific provenance indicators can be used in combination with QGSTA to assess whether it is possible to further reconstruct the environment from which samples were derived. Table 9 details geographical location information derived from the identification of different types of material in samples recovered from mock device components, as well as further analysis which could be carried out to provide additional information as to the geographical location of activities in the supply chain. Such information could be combined with other data to produce a multi-source intelligence product.

Although the material recovered from device components can be used to indicate potential environments involved in the supply chain, it is vital to consider that secondary transfer [47] and transportation of material from source site to another location

Table 9
Provenance information derived from the identification of different materials in samples recovered from mock device components, as well as additional analysis that could be carried out to provide information as to the geographical location of activities in the supply chain but that was beyond the scope of this study.

Material recovered	Provenance indication	Potential for additional analysis
Paint		Analysis of the paint to identify if it is automobile paint, if so its chemical composition can be compared against automobile paint databases to exclude, make, model and year, in an endeavour to identify the car to which the paint is derived
Clasts of chalk	Geographical location with a bedrock geology of chalk and/or a fluvial/alluvial environment depositing chalk clasts	^{87}Sr/^{86}Sr isotope analysis of the chalk clasts – comparison against ^{87}Sr/^{86}Sr sea level curve will provide a crude estimate of potential sources of the clasts through exclusion
Tarmac	Location with tarmac surfaces e.g. road, pavement, car park, driveway	
Charcoal	Location where there has been a fire or burning of some sort	
Brick	Locations with brick structures	
Fibres		Microscopic analysis of the fibre to identify type (naturally occurring, synthetic etc), and chemical analysis of the fibre to establish composition of the dye, both of which may help to identify a source
Animal hair		Oxygen isotope analysis of the hair to identify through exclusion, potential water sources from which the animal was drinking
Transparent spheres	If reflectance spheres, would indicate location with road paint/road signs e.g. roads, car parks	Elemental analysis to establish whether fly ash particles or reflectance spheres from road paint
Plant material		Hand/microscopic identification of the plant/seed/flower/pollen type → Comparison of identified material against vegetation maps, to exclude areas from which the material is not derived
Organic material		Gas chromatography analysis of the organics to obtain alkane profile, which may offer an indication of the type of vegetation and land use from which the organic material is derived [44]
Insect shells		Identification of the insect, and the locations/habitats in which they occur

cannot be ruled out. Moreover, specific features may represent a previous or historic environment, for example alkane profiles of organics recovered may represent the vegetation which previously grew in the area, from which they are derived, owing to them residing in soil for substantial periods of time [48]. All forensic techniques possess limitations, and consideration and presentation of them is essential during interpretation and communication to decision makers, whether for CJS or intelligence purposes.

The effectiveness of seek and find operations is understandably dependent upon the type of material recovered from devices, the availability of relevant comparative databases, both of which are likely to be case specific, as well as the availability of techniques which are capable of distinguishing different geographical sources within a single sample. However, in carrying out such pilot study, it is possible to provide an initial evidence base for the use of geoforensic analysis, to derive intelligence as to the geographical location of IED supply chain activities.

5. Conclusions

This study is the first to address the application of geoforensic analysis to the exploitation of IEDs for C-IED efforts. A number of significant findings have been presented:

1. Materials derived from multiple nodes of the simulated IED supply chain were transferred and preserved on device components. This could potentially facilitate identification of the geographical location of IED supply chain activities, which in turn may support an attack on the IED network.
2. Sampling from different locations on recovered devices is crucial to establish whether different components preserve signals related to different nodes of the supply chain, and/or signals derived from a single node.
3. Transfer of material between different provenances i.e. secondary transfer has the potential to produce misleading intelligence.
4. Mixed provenance signals preserved on devices favour analytical approaches which can detect multiple sources within a sample to prevent false positive or negative exclusions during interpretation.
5. PSA should typically only be used as a descriptive tool in a forensic inquiry due to both the inability to distinguish individual provenance signals in a mixture, and the potential occurrence of small scale spatial variability, and short term temporal changes in particle size distribution. Such factors may lead to false positive of negative exclusions.
6. The improvised nature of IEDs introduces significant complexity and variability factors when seeking to establish an evidence base for the interpretation of information derived from such devices.

This preliminary study has demonstrated the expansion of the application of geoforensic analysis to address the pressing international security challenge that IEDs pose. It has been established that there exists the potential to exploit geoforensic analysis for intelligence that may help to identify links between places, people, devices and vehicles in the IED supply chain. This could ultimately assist C-IED efforts, in attacking the networks that facilitate the distribution of large numbers of IEDs. Application of geoforensic analysis to actual IED exploitation cases is necessary to test the efficacy of this innovative approach in casework scenarios.

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