Geophysical Investigations of WW2 UK air-raid shelters

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Word count: 8,616

Geophysical Investigations of WW2 air-raid shelters in the UK

In the prelude to the Second World War, the British government prepared for an aerial onslaught that, it was predicted, would raze cities to the ground and cause mass casualties. By 1938, the Air Raid Precautions Act ensured that Britain would be ready for aerial attack, and formally adopted a principle that the protection of the population from bombing would be through dispersal of the population. This meant evacuation, and protection on a local scale, rather than the construction of deep shelters intended to protect the population en-masse. As a result, such air raid shelters that were produced were the responsibility of the local authority, and all too often this meant that that responsibility devolved to the householder, who was expected to create bomb- and gas-proof rooms. It also means that the archaeological record of air raid shelters is relatively rare, with the distinct possibility that such features are under threat.

As such, this paper reports the results of non-invasive geophysical surveys over three different air-raid shelter sites, located in Stoke-on-Trent and London. Multi-technique geophysical surveys were required to locate, identify and characterise the shelters, as well as to determine optimal geophysical detection method(s) and equipment configuration(s).

Study results found that the three intact, Stanton-type pre-fabricated shelters in Stoke-on-Trent could be successfully located by ground penetrating radar, electrical resistivity, magnetometry, gravity and electromagnetic methods. The partially demolished shelters in Central London provided a geophysical response (from EM and GPR) but could not be further characterised. Finally, the intact, mass public-type shelter in South London were detected by EM and GPR methods. Subsequent intrusive investigations confirmed London site interpretations.

This study shows that these important, but hitherto-neglected, wartime shelters can still be in good condition and near-surface geophysical surveys can detect and characterise their location, size, burial depth and even their construction materials. The outcomes suggest that geophysical surveys can be used to help assess the integrity of such buried structures and help to bring WWII British history into the wider scientific community and the public domain.

Keywords: geophysics, WW2, air-raid shelters, The Blitz, United Kingdom

INTRODUCTION

Air Raid Shelters are a relatively neglected component of the numerous archaeological studies of conflict that have arisen over the last twenty or so years. While there are some notable exceptions (e.g. see *Moshenka 2007; Thomas 2016*), in most cases, air raid shelters constructed during the two world wars have been neglected, as most archaeological projects have concentrated on trenches, dug-outs, foxholes and battle scars of front-line conflict (see, for example, *Doyle et al. 2001, 2002, 2005; Everett et al. 2006; De Meyer and Pype, 2007; Brown and Osgood 2009; Masters and Stichelbaut, 2009; Banks, 2014*; *Banks and Pollard, 2014; Doyle 2015, 2017*), prisoner of war camps and activities (*Moore, 2006; Pringle et al. 2007; Doyle, 2011, Doyle et al. 2013*; *Schneider 2013; Rees-Hughes et al. 2016*); or the hospitals, airfields and other logistics of war (e.g. *Dobinson et al. 1997; Schofield, 2001; Passmore et al. 2013; 2017; Capps Tunwell et al. 2015*).

Despite the increasing diversity of study of wartime sites, Home Front sites have been somewhat neglected. While the *Defence of Britain Project* of the early 2000s (e.g. see *Schofield, 2004*; *Foot 2006*) surveyed the remaining WW2 anti-invasion fortifications of Britain, consisting of various concrete fortifications, defence lines and other positions, but there has been little consideration of civil 'passive defence' measures (though see *Thomas, 2016*). The UK's WW2 Civil Defence response was large, yet there has been little in the way of detailed survey of surviving anti-air-raid structures, many of which exist by chance (e.g. *Thomas, 2016*; see illustrations of shelters and other features in *Brooks, 2006; Bright, 2016*).

The first steps to achieving this is through the identification and recognition of surviving structures, built for passive defence in the built environment. As discussed below, during WW2 there was a diversity of approach to the maintenance and construction of air raid shelters, or of protected spaces and refuges, and those approaches changed throughout the war itself. It is not surprising, therefore, that this has meant that the infrastructure of air raid shelters is complex, and that their record in the archaeological record is disparate, with former air-raid shelters degraded, demolished, partially or wholly removed or filled in (e.g. *Moshenka, 2007*). While some celebrated schemes are protected by official listing status, others are more vulnerable to destruction (see *Schofield, 2004; Thomas, 2016*). For instance, it is thought that with some 23 million issued and installed, just 6% of domestic 'Anderson Shelters' survive today (*O'Brien, 1955; Schofield, 2004*). Any remaining shelters in the urban environment are therefore a limited resource and a significant reminder of a crucial time in European history.

For these reasons alone, any investigations that seek to locate, identify, and characterise WW2 air raid shelters will be making a significant contribution to the wider study of these features. As part of the investigations of wartime sites, near-surface, multi-technique geophysical surveys have become increasingly popular (see, for example, *Gaffney et al. 2004; Everett et al. 2006; Pringle et al. 2007; Fernandez-Alvarez et al. 2016; Rees-Hughes et al. 2016*), due to their capability to locate and characterise buried objects for subsequent intrusive investigations. Given the relative rarity of existing air raid shelters, the use of the non-invasive surveys employed here represent good practice and demonstrate what can be done to locate and characterise them. This also has greater significance due to the fact that air raid shelters could present a potential hazard to modern ground engineering activity, due to their construction materials and the potential for encountering subsurface voids.

As such, this paper describes multi-technique geophysical site investigations of known Second World War (WW2) air-raid shelters in three different sites in the UK, comprising subsurface prefabricated concrete sectional ('Stanton') shelters located in Stoke on Trent, and two subsurface brick and concrete shelters in London. These sites are typical of the diversity of subsurface shelters dating from the post-'Big Blitz' period of 1940-41. The aims of this paper are to record these shelters at the three study sites, document the geophysical and limited intrusive site investigations carried out, determine the optimum geophysical technique(s) and equipment configuration(s) and discuss how other researchers can utilise geophysical surveys to locate WW2 air-raid shelters in the future.

WW2 AIR RAID SHELTER POLICY, TYPOLOGY AND DESIGN

The development of air raid shelters dates back to the First World War (WW1), with the advent of aerial bombing, and the destruction of property and life that accompanied it (*O'Brien, 1955; Thomas, 2016*). With little choice, air raid shelters became *ad hoc* affairs, and in London, railway arches and underground railway tunnels were used as shelters for the first time (*Gregg, 2001*). Railway arches in particular were vulnerable to bomb penetration at their weakest part through the railway track bed itself (this would have tragic consequences when deployed during WW2, see *Fitzgibbon, 1970*; *Bright, 2016*).

The Air Raid Precautions (ARP) Department was formed at the Home Office in response to the rearmament of Germany, and from 1 April 1935 it was to direct the development of passive air defence in Britain, in response to the growing threat (*O'Brien, 1955*). The possibility of aerial attack was magnified in stark reality by the bombing of Spanish cities such as Barcelona in the late 1930s (*O'Brien, 1955; Moshenka, 2010*). The Air Raid Precautions Act of 1937 established the principles of the relationship between the Government's responsibilities, those of local government and the average citizen to provide for their own safety in wartime.

On 1 January 1938, the new ARP Act came into force, and it was the Munich crisis of September 1938 that confirmed the inevitability that these services would be needed. The subsequent Civil Defence Act 1939 empowered local authorities to take on the responsibility for the construction of shelters. One of the most enlightened was the London Borough of Finsbury, which retained the noted architectural firm of Tecton – to examine the issue in order to provide a scheme for the complete protection of the people of the Borough (*Tecton, 1939;* see also *Baker, 1978*). This examined the provision of basements and other shelters, and envisaged the construction of 14 deep shelters based on a spiral ramp that could be used for some 7,600 - 12,600 people. Finsbury sought grant-in-aid from the Home Office on the basis of their ambitious scheme on 6 February 1939, but it was never enacted.

This meant that in the run up to WW2 there was no official policy that saw the construction of deep or even sub-surface air raid shelters. Instead, 'dispersal' – the idea of dissemination of the population – was Government Policy with regards to the protection of the population from aerial attack (see *Deedes, 1939; O'Brien, 1955; Fitzgibbon, 1970; Baker, 1978; Wade, 2011*). Its purpose was to prevent the mass concentration of people in shelters that would be therefore vulnerable to attack. The policy ensured the evacuation of school-age children, mothers and the elderly from nine 'evacuable areas' of Britain, considered to be the main targets – a prediction that, for the most part, was correct (Table 1) (*Anon, 1939; Civil Defence, 1939a; Ministry of Home Security, 1942; O'Brien, 1955; Collier, 1957*).

	Evacuable areas	Major Raids 1940-41	Bomb tonnage
a	London; Co. Boroughs of West Ham & East Ham; Boroughs of Walthamstow, Leyton, Ilford, Barking, Tottenham, Hornsey, Willesdon, Acton, Edmonton	71	18,291
b	Medway towns of Chatham, Gillingham & Rochester		
c	Portsmouth, Gosport & Southampton	7	1,334
d	Birmingham & Smethick	8	1,852
e	Liverpool, Bootle, Birkenhead & Wallasey	8	1,957
f	Manchester & Salford	3	578
g	Sheffield, Leeds, Bradford & Hull	4	948
h	Newcastle & Gateshead	1	152
i	Edinburgh, Rosyth, Glasgow, Clydebank & Dundee	5	1,329

Table 1: 'Evacuable areas' and Major raids during the 'Big Blitz' of 1940-41, sourced from Civil Defence (1939a); O'Brien (1955); Collier (1957).

The same policy dictated that there would be no construction or excavation of 'deep shelters' on the basis that it would be impractical to excavate sufficient shelter space for the population of target areas. In addition, there was concern that such shelters would lead to the development of what was known as 'shelter mentality', by which, it was predicted, the population would stay semi-permanently below ground, with consequent loss of productivity (*O'Brien, 1955; Fitzgibbon, 1970;* see *Jones et al. 2004; Jones, 2016*). This approach was subject to intense criticism by a group of scientists and other intellectuals who viewed the Government's response to be flawed in the years before the start of the actual conflict (e.g. *Cambridge Scientists, 1937; Haldane, 1938; O'Brien, 1955*). This meant, wherever possible, seeking shelter at home, making use of shoring, as well as the development of '*a steel structure, capable of mass production*' which could be erected at home (*O'Brien, 1955*, p. 171). This structure would ultimately become known as the Anderson Shelter, issued to poorer people free of charge, but as it was partially dug in, it was dependent upon garden space being available (*Air Raid Precautions, 1939; Civil Defence, 1939b; Ministry of Home Security, 1940*).

Often there were mixed schemes, as in Dartford, Kent (*Mike Still, Dartford Borough Museum: Personal Communication, 2018*). The minutes of Dartford Council's Air Raid Precautions Committee for April 1939, identifies the need to '*prepare a list of available basement and cellarage accommodation*', in response to the need for shelters, and seven shops were identified that could be used in this way. Surface shelters were provided to meet a shortfall, identified in the minutes of July and August 1939, and intended to house 2,900 people. Dartford Council's General Purposes Committee (28 September 1939), also recognised the need for trench shelters, which were dug in a number of sites with open spaces, and which were strengthened as the war proceeded. A single railway arch was also put aside for air raid use. As can be seen from this discussion, there was no consideration of deep shelters, in line with Government policy. Notwithstanding that, it is known that some schools (West Hill, Dartford Grammar, etc) did have underground shelters, and this again shows the possibility of such shelters (cf. *Moshenka, 2007*) existing, at variance with official policy.

Nevertheless, the policy relating to the construction of deep shelters was modified after the period of the 'Big Blitz' in 1940-41 (*O'Brien, 1955*), leading to the development of some deep shelters in vulnerable parts of Britain from 1941 onwards (*O'Brien, 1955; Thomas, 2016*). The intention was to protect the population and workforce in some those parts of the country with vital dock and industrial components, and as such it was never fully suggested that there would be a move to complete underground protection.

In his 1938 book *A.R.P,* and in the light of the Governments opposition to deep shelter provision, the scientist J.B.S. Haldane identified (and criticised) the available shelter types, using his criticism to defend his assertion that deep shelters alone were essential for the protection of the public. Though Haldane's assertions were not acted on until the post ‘Big Blitz’ period of September–May 1940-41, Haldane’s shelter types may be usefully compared with those employed during the war (Table 2; see *Rathbone, 1942*, for a US perspective).

	Shelter Type	**Description**	**Usage**	**Archaeological legacy**
1	**Refuge-rooms in ordinary homes**	**Surface**: Shoring and strengthening, ground floor rooms. Strengthened rooms were intended to remain intact. The later steel framed ‘Table’ or Morrison shelter (*Ministry of Home Security 1941*) was intended to do the same job. Morrison shelters 2m long, 1.2m wide, 0.75m high. Steel construction, spring base and removable mesh sides for shrapnel protection	Steel shoring was made available to strengthen as ‘strutted rooms’, including public buildings. Most refuge rooms were intended, initially, as protection from gas attacks (*Haldane 1938; Home Office, 1938; Deedes, 1939; Ministry of Home Security, 1939, 1940a*)	**Moderate to Low.** There are surviving examples of Morrison shelters, though few if any in situ. Most were used for scrap metal in post-war period.
2	**Steel frame and other strong buildings**	**Surface**: Ferro-concrete buildings, stone buildings	These were often modern buildings, shops, restaurants, car parks and the like that were pressed into service. In some cases these proved inadequate, as in the bombing of the Café de Paris in London, 1941 (*Fitzgibbon 1970*).	**Moderate.** Buildings bearing external blast damage is visible across the UK.
3	**Splinter-proof rooms**	**Surface**: Rooms with thick walls Capable of resisting bomb splinters	As 1, above	**Low.** As 1, above
4	**Cellars & strong rooms**	**Subsurface**: cellars with vaulted ceilings and with sufficient earth cover; they can be strengthened.	As above steel shoring was made available to strengthen as ‘strutted rooms’, including public buildings. Haldane (1938) commented that these were ‘rare in Britain’.	**Low to Moderate**. Surviving strutted basements are likely to be rare due to ‘post-war scrap drives’ (Thomas, 2016, p. 11). There are existing examples in Westminster, London, complete with shelter signs (see *Brooks 2011*)
5	**Trenches and shallow dug-outs**	**Subsurface**: partial protection only. Dug in parks and open spaces. Trenches were later strengthened and adapted with concrete and a variety of other materials (*O’Brien 1955; Thomas 2016*).	Trenches were dug in the prelude to war and were strengthened and used throughout the war, and adapted, and often roofed , sometimes with parabolic roof sections. Stanton Shelters, made from parabolic concrete sections, are examples of this	**Low to Moderate.** Surviving open trenches are unlikely, but given the fact that they were excavated within public parks and other open spaces, there is a

		Trenches were typically up to 2.14 m wide, some 10-20 m long and no less than 2 m deep. Stanton shelters are of this type, 9m long, 2.3m wide, 4m high. Pre-cast steel; reinforced concrete modular design (Anon nd)	type, though they were most often used for military purposes (*Anon, n.d.*)	likelihood of an archaeological record, discoverable by geophysical techniques.
6	**Deeper dug-outs and special shelters**	**Subsurface**: 'hillside dugouts'; 'special steel shelters'.	These included tunnels and caves, dependent on location, which could be pressed into service as shelters, such as Chistlehurst Caves in Kent, and other suitable locations (*Thomas 2016*).	**Moderate** Many pre-existing tunnels, such as Chistlehurst Caves, which were used as shelters during the war, survive.
_	**Anderson Shelter**	**Subsurface:** The Anderson was in effect a special shelter (see above). Anderson shelters were 2m long, 1.2m wide, 1.8m high. Curved galvanized corrugated steel sheets bolted and secured to baseplate	The Anderson shelter was distributed to huge numbers and was intended to withstand the blast of a 500lb bomb, though not a direct hit. It was extremely effective (*O'Brien 1955; FitzGibbon 1970; Thomas 2016*), Flooding was a problem (*Ministry of Home Security 1940b*).	**Low** Though 3.6 million were distributed, few survive in situ
7	**Underground railways and other tunnels**	**Subsurface**: deeper 'Tube' tunnels; some are shallow	The Underground railways, 'Tubes', were targeted by would-be shelterers in WW1, and again in WW2. Official policy was against this, but this gave way under public pressure (O'Brien 1955; Gregg, 2001).	**High** Most tube lines and stations are still in operation, though others, such as the Aldwych, that were used during the war are now inaccessible.
8	**Tunnels made for shelter purposes**	**Subsurface**: excavation of special tunnels, use of other tunnels such as sewers	Short tunnels were excavated in the post-Big Blitz period in vulnerable locations. This is the case in vulnerable port towns, e.g. Birkenhead, Bristol, Dover and Ramsgate, as well as other inland targets (Thomas 2016). Extensions of some tube stations were made in this period. In the post-Big Blitz period, eight extensions were made at the following stations: Clapham North, Clapham Common, Clapham South, Stockwell, Goodge Street, Camden Town, Belsize Park and Chancery Lane (Gregg 2001)	**High** Those tunnels made during the war, after the 'Big Blitz' period, should be still extant. It is certainly the case for the Tube extensions, with many used for other purposes, such as secure storage (Goodge Street).
9	**Bomb-proof underground shelters other than tunnels**	**Subsurface**: modular concrete and other subsurface structures	Bold plans were made pre-war for large schemes in some boroughs (see Tecton 1939). Small scale schemes were carried out in some immediate pre-war developments, such as	**Moderate–High** Constructed according to local conditions, political and geographical, they vary in extent

			St Leonards Court, Richmond, with capacity for 48 people (Thomas 2016).	and development. Many may be lost to infill, and could be identified by geophysics.
10	**Conical buildings**	**Surface**: Ferroconcrete towers, as built in Germany	As far as can be determined, not used in the UK	–
-	**Surface shelters**	**Surface**. Haldane does not mention these. Surface shelters varied from small rectangular or square constructions to accommodate 4–6 people, through to those to accommodate a maximum of 50. They could be built to a modular design with 50-person capacities in each section. They had 12” thick brick walls and a 6” reinforced concrete roof. (Thomas 2016)	Surface shelters were intended to supplement the Government ‘stay at home’ policy, and were constructed such that they could accommodate<50 people to reduce mass casualties. Mistrusted, they were sometimes built of inferior materials (O’Brien 1955; FitzGibbon 1970; Baker 1978). They were unlikely to survive direct hits (e.g. see Brooks 2011)	**Low-Moderate** Surface shelters were often destroyed in the postwar era, but some survive, pressed into service as garden sheds (small) or garages (e.g. Brooks 2011; Bright 2014; Thomas 2016)

Table 2: WW2 Air Raid Shelter types in the UK (based on Haldane, 1938)

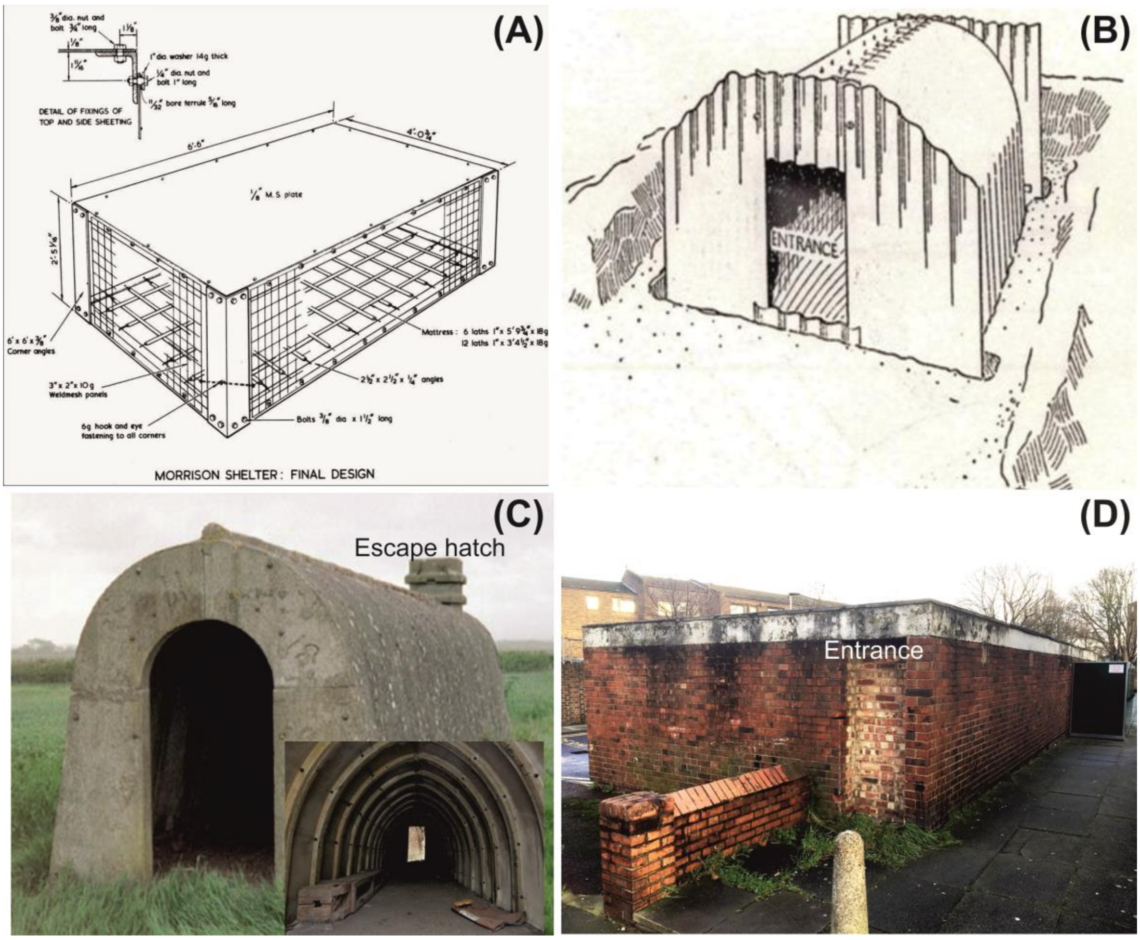

Figure 1. (A). Schematic diagram of the Morrison emergency indoor shelter where households lacked cellars/gardens or other safe places (*Ministry of Home Security, 1941*). (B) Schematic diagram of an Anderson household garden shelter, commonly half-buried, comprised of curved and bolted corrugated steel sections and a large baseplate (*Home Office, 1939*). (C) Photographs of a Stanton shelter, composed of bolted-together, pre-cast steel reinforced concrete sections and escape hatch, mostly constructed in airfields, this sub-aerially exposed one located in Kirkbride, Scotland (*Barnes, 2005*). (D) Example of surface shelter design, comprising a modular form with brick walls and thick concrete roof; this one, in south east London, has been preserved for use as garages (Image: Steve Hunnisett). Such shelters were unpopular due to early bombing raids causing heavy casualties (*FitzGibbon, 1970; Baker, 1978*).

Table 2 identifies the potential archaeological legacy of air raid shelters, a theme developed by other authors (e.g. *Schofield, 2004; Thomas, 2016*). An analysis demonstrates that, whereas the archaeological legacy of most early war 'Big Blitz' shelters is low – including as it does most surface shelters, and temporary shelters such as Andersons or Morrisons – others are potentially higher, such as trench shelters cut in public parks, and other subsurface shelters, some of which were developed privately at variance with Government policy. It would therefore be expected that with the right conditions they would be discoverable by geophysical techniques. Greater still are deeper dugouts or shelters, or modular buildings such as the concrete 'Stantons', prefabricated by the Stanton Iron Works during the war (*Anon, n.d.*). Constructed from the pre-war to the post-Big Blitz, these are often variable in extent and construction, and represent a resource that should be capable of excavation, where known (e.g. *Moshenka,* *2007*), or identified using geophysical techniques. This is now demonstrated with three case studies in air-raid sensitive (‘evacuable’) areas of England.

SITE 1: ABBEY HULTON, STOKE-ON-TRENT, STAFFORDSHIRE, UK

Three Stanton-type, half-sunken WW2 air-raid shelters were known to be adjacent to the exposed ruins of Hulton Abbey, in Abbey Hulton, Stoke-on-Trent, Staffordshire (Fig. 2). Two of the shelters fall within the bounds of the Scheduled area of the Abbey ruins. Constructed by the Stanton Ironworks Company, its concrete plant was 'turned over to concrete air-raid shelters, of which subsequently 100,000 tons were manufactured, principally for the Air Ministry' (*Anon, n.d., p. 40*). Given their intended end use, Stanton Shelters are requisitely rare in civilian locations. The shelters were specifically constructed to shelter pupils from Carmountside Primary School, which occupied much of the former Abbey site between 1938 and 1987. Present school records (now on a different site) indicate that shelters were used seven times during WW2 (*Anon, 2010*). The shelters were still visible on aerial photographs taken in 1963 and 1974 (Fig. 3). The local geology of the site is a clayey loam overlying mudstones, siltstones and sandstone bedrock of the Carboniferous Lower Coal Measures Formation.

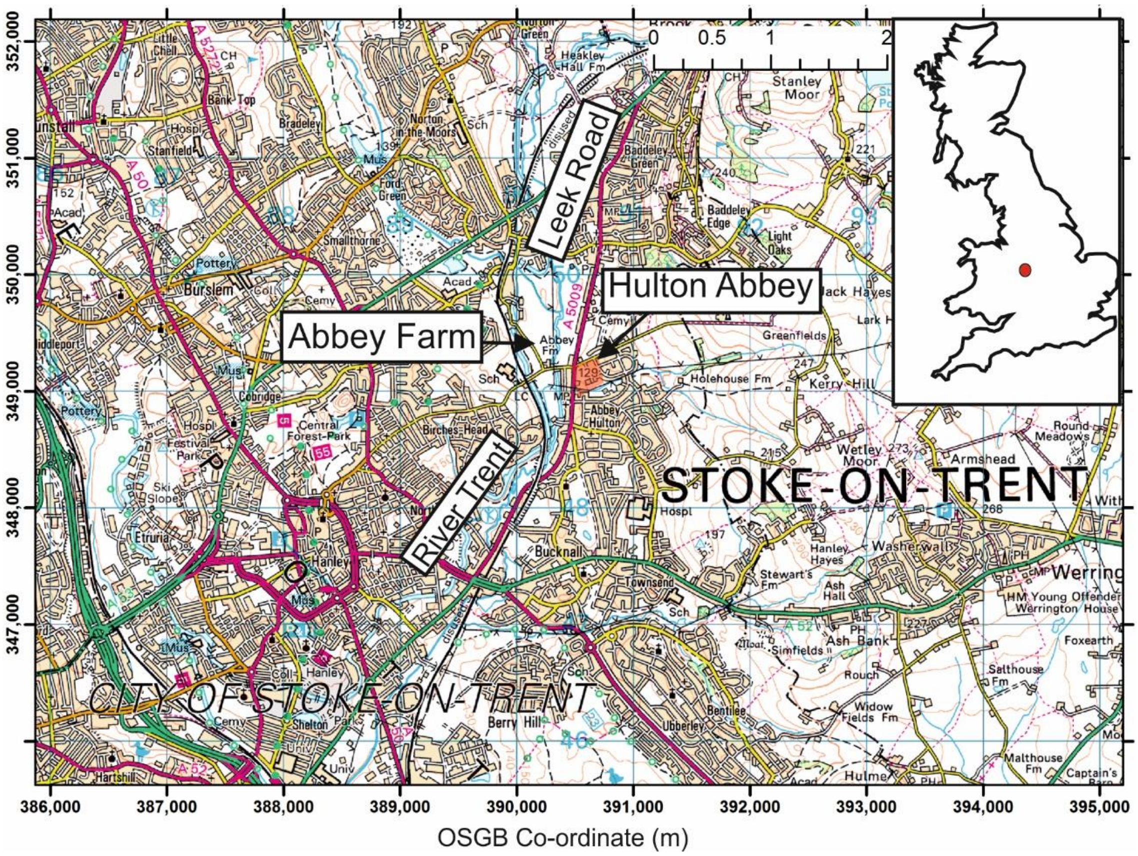

Figure 2. Location map of Hulton Abbey, Stoke-on-Trent, Staffordshire, with UK location (inset). Map courtesy of EDINA™ DigiMap (2016).

Figure 3. (A) 1963 and (B) aerial site photographs showing the now-demolished Carmountside Primary School buildings, Hulton Abbey ruins and the three air-raid shelters visible in the study site in Stoke-on-Trent, Staffordshire, UK (modified from *Wise, 1985*).

An initial site investigation was undertaken in March 2017, determining that the soil was a silty loam type (10YR/2/2 Munsell colour). There were several mature trees and ground vegetation cover, together with metal fences at the site borders. The air-raid shelters were observed to be still present, 9m long, 2.3m wide, evenly spaced and partially buried, with the middle shelter having an exposed concrete escape hatch with metal ladder (Fig. 4). This information suggested that these are Stanton-type shelters. A simple topographical survey was undertaken to map the modern site features and establish a key 2D profile line (Fig. 5).

Figure 4. Abbey Hulton site photograph (looking North) in March 2017 with view of the Stanton air-raid shelter's escape hatch.

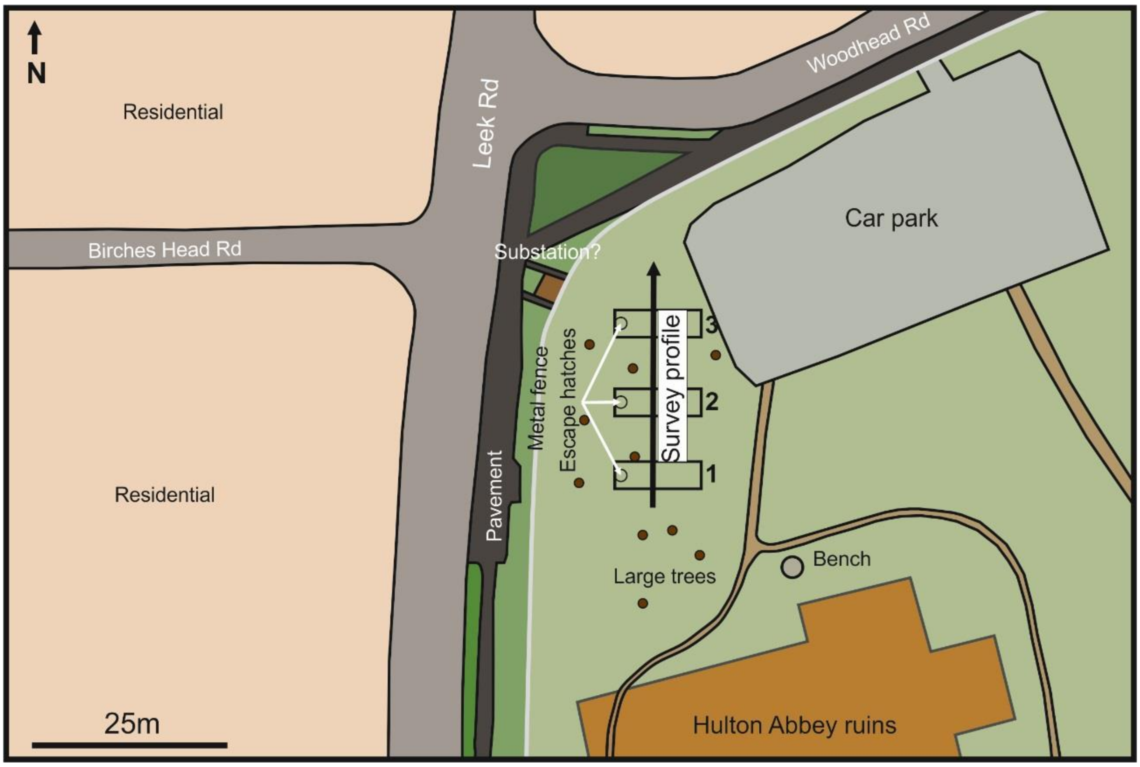

Figure 5. The Abbey Hulton study site 1 site map, Stoke-on-Trent, Staffordshire, UK (see Fig. 2 for location). The three Stanton type air-raid shelter positions marked 1-3 (Fig.4 taken from 2 escape hatch), together with the key 2D survey profile (and survey direction arrowed).

SITE 1: DATA ACQUISITION AND PROCESSING

A survey line was established perpendicular to the three air-raid shelters, passing approximately through the centre of them (Figure 5), and the dense vegetation cleared to allow relatively easy access for the geophysical surveying equipment.

Ground Penetrating Radar Survey

GPR surveys are the commonly used in archaeology, as they can detect buried objects up to 10 m below ground level in ideal conditions (see *Sarris et al. 2013; Dick* *et al. 2015*). Following initial onsite testing of the GPR PulseEKKO™ PRO system using available 250 MHz, 500 MHz and 1000 MHz frequency antennas to determine the most suitable frequency for investigation; the 1000 MHz frequency was discarded due to the lack of penetration and clarity at depth. The 250 MHz frequency, with a fixed antenna-offset of 0.38m, was used to acquire a 2D profile (Fig 5). Measurement spacing was 0.05 m, a 120 ns time window and summing 32 recordings at each survey position. The lines were then surveyed using the 500 MHz frequency, fixed antenna-offset of 0.23m, was used using a measurement spacing of 0.025 m, a 90 ns time window and the same summing 32 recordings. A standard sequential data processing sequence was applied to each 2D profile in Sandmeier™ REFLEXW v.8.5 software. This consisted of; 1) Selecting the first positive amplitude response to move start time to 0 ns, dynamic correction to adjust for antenna geometries, bandpass butterworth to remove high and low frequencies (frequency ÷ 2, frequency × 2), background removal (subtracts mean of all traces from each trace), Automatic Gain Compensation (AGC) gain to counteract signal attenuation and finally a conversion from Two-Way Time (ns) to Depth (m) using an average site velocity of 0.1 m/ns determined from analysis of hyperbolic reflection events (see *Milsom & Eriksen*, *2011* for background).

Magnetic Gradiometry Survey

Magnetic surveys arethe most common in archaeological site investigations (see *Masters and Stichelbaut, 2009; Lowe, 2012; Fassbinder, 2015)*. Following calibration in a magnetically quiet area of the site, a Bartington™ Grad601 Single Axis fluxgate gradiometer was used to acquire magnetic gradient data at ~0.1 m sample intervals along the survey line (Fig. 5). A rejection value of 50 Hz was chosen and a 1000 nT range due to the busy urban site nature. A standard processing sequence was applied using Microsoft Excel software. Anomalous data points due to acquisition issues are removed, termed 'despiking', and long wavelength trends in the data removed, 'detrending' (see *Milsom & Eriksen*, *2011* for background).

Electro-Magnetics Survey

Electro-magnetic methods are commonly used in archaeological investigations (see *De Smedt et al., 2014; Gaffney, 2008*), as sensors are easily manoeuvrable, and data is collected rapidly *(see Milsom & Eriksen, 2011* for details*).*

A GF Instruments™ CMD mini-explorer was used to collect in-phase and quadrature data using both vertical and horizontal dipole configurations. Different dipole spacings effectively allow different penetration depths, 1m and 1.8m for Vertical Dipole alignment (VMD) and 0.5m and 0.9m for the Horizontal dipole alignment (HMD). The instrument self-calibrates and acquired data at ~0.1m intervals along the survey line. The data were despiked and detrended using Microsoft Excel software.

Bulk-Ground Electrical Resistivity Survey

Bulk ground electrical resistivity methods have also been commonly used in archaeological investigations *(see Thacker and Ellwood, 2002; Terron et al., 2015; Dick et al. 2017).* Although the investigation depth is dependent on the probe spacing, generally the method is cheap, easily manoeuvrable, and data is rapidly collected *(see Milsom & Eriksen, 2011* for details*).*

After testing with different probe spacings and sample intervals, a Geoscan™ RM15-D Resistivity Meter, using a parallel Constant Separation Traverse (CST) twin-probe array setting, was used with probe separations of both 1.0 m and 1.5 m, to acquire resistance readings at 0.25m sample intervals over along the survey line. The data was despiked and detrended using Microsoft Excel software.

A CAMPUS™ TIGRE meter was also used to collect a 2D Electrical Resistivity Imaging (ERI) 2D profile along the survey line, using 38 electrodes at 1 m spacing in a Wenner array configuration due to its near-surface sensitivities. After initial testing that relatively consistent contact resistances were being recorded at each electrode, a 2D profile was collected. Data processing steps were applied using Geotomo™ Res2DInv v.3.55. These were removing anomalous data points, an inversion using a least-squares best-fit algorithm with a threshold set to 5% misfit and displayed using a logarithmic colour contoured scale.

Micro-Gravity Surveys

Micro-gravity surveys are rarely used in archaeological investigations but are commonly used in geotechnical site investigations, for example, when looking for near-surface voids (see *Pringle et al. 2012*) or coal mineshafts (see *Pringle et al. 2008*).

A Scintrex CG5 micro-gravimeter was used to collect gravity observations on 2 m intervals along the survey line, collecting data for 90s at each position, with three repeated readings at each survey point. Base station observations were collected at the nearby car park (Fig. 5) before and after the half day survey to correct for any gravitational changes due to tides and instrumental drift following standard procedures (see *Milsom and Eriksen*, *2011*). Standard data processing steps were undertaken using in-house Microsoft Excel spreadsheets. This comprised correcting for site latitude, correcting for tidal variations/instrument drift using base station polynomial drift values, Free Air and Bouguer corrections (using a density value of 1.8 g/cm^3) were used to compensate for elevation changes, repeat gravity reading were averaged and anomalous points removed and finally a background linear trend removed (see *Milsom & Eriksen*, 2011 for background).

SITE 1 RESULTS

GPR Results

GPR results for both the 250 MHz and 500 MHz frequency 2D profiles show three strong hyperbolic reflection events that correspond to the three air-raid shelter positions, presumably caused by a strong dielectrical permittivity contrast between the background soil, the pre-cast concrete shelters and the air-filled voids inside (Fig. 6). The tops of the shelters were calculated to be between 0.5 m – 1 m below present ground level. Multiple reflections were also observed below each first shelter response, attributed to a ringing multiple effect, with made-ground between each shelter (Fig. 6). The 250 MHz frequency dataset produced more clear reflection events over the target features.

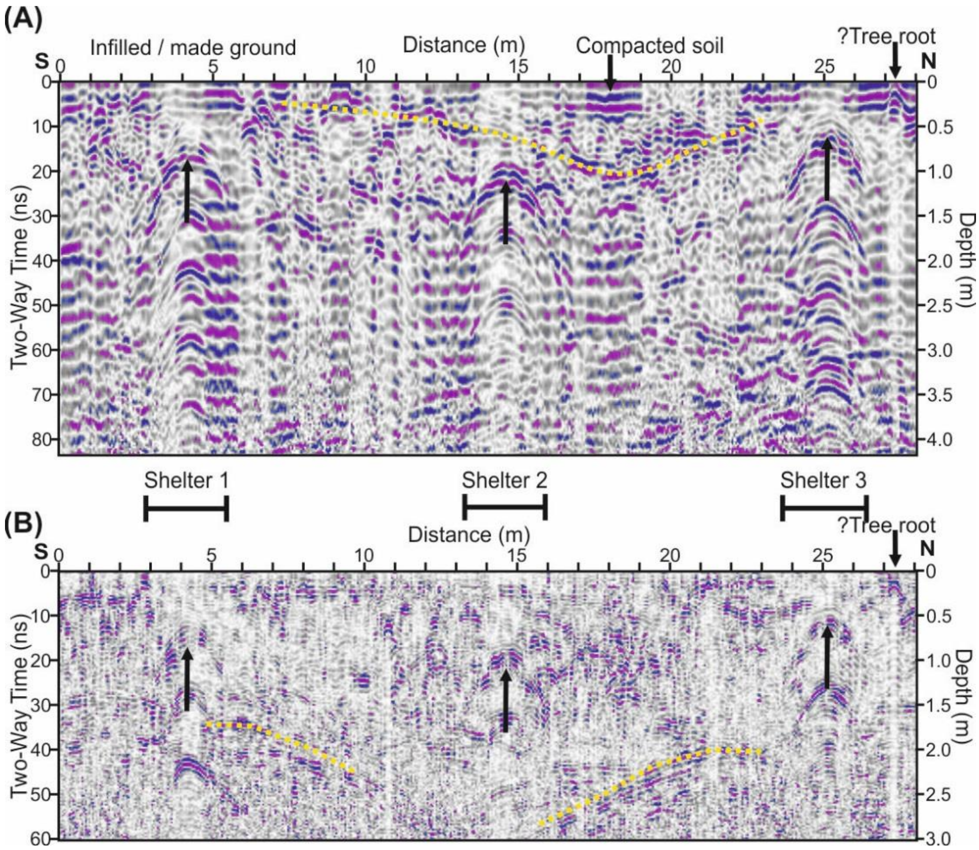

Figure 6. (A) 250 MHz and (B) 500 MHz frequency GPR 2D processed profiles acquired over the survey line (Fig. 5), with the location of the three Stanton-type air-raid shelter positions marked (arrows) and other pertinent features.

Magnetic Gradiometry Results

The magnetic gradient results showed a large range of about 1,800nT over the surveyed profile, with three relatively large and similar amplitude and wavelength anomalies present, compared to background values; their mid-points could be easily correlated to the three air-raid shelters (Fig. 7). Air-raid shelter 3 has the largest amplitude, although note an above-ground metallic object was present here (Fig. 4).

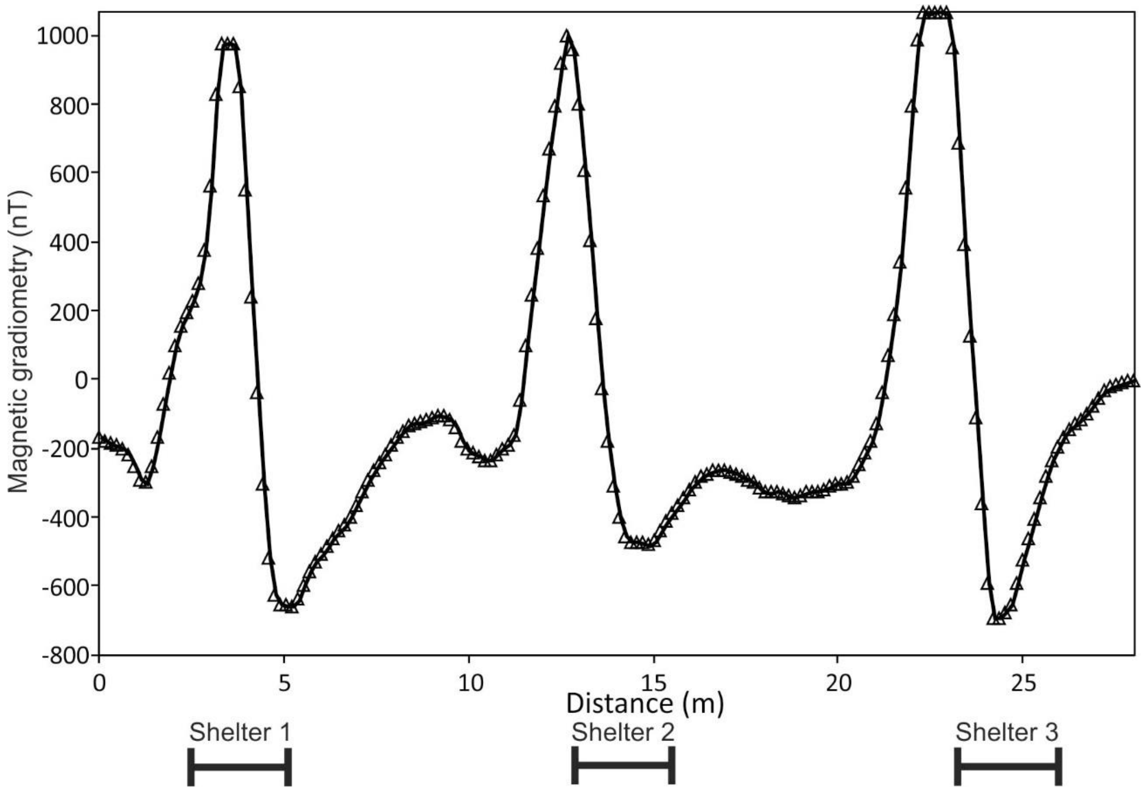

Figure 7. Magnetic gradiometry processed profile acquired over the survey line (Fig. 5), with the location of the three Stanton-type air-raid shelter positions marked.

Electro-Magnetics Results

All in-phase and quadrature processed results of respective survey modes showed three clear conductive anomalies that could be correlated to the known Stanton air-raid shelter positions (Fig. 8). In-phase anomalies were 100-200 ppt higher than background values, with the respective deeper depth quadrature anomalies ranging from 10 mS/m – 30 mS/m higher than background values (Fig. 8). Shelter 2 had half the anomaly strength compared to shelters 1 and 3 (Fig. 8), suggesting that it had less conductive material present. Note the metal boundary fence (Fig. 4) did not appear to be interfering with survey results. The coils measuring relatively deeper penetration depths were also uniformly gaining high relative anomaly strengths than the relatively shallower penetrating coils (Fig. 8).

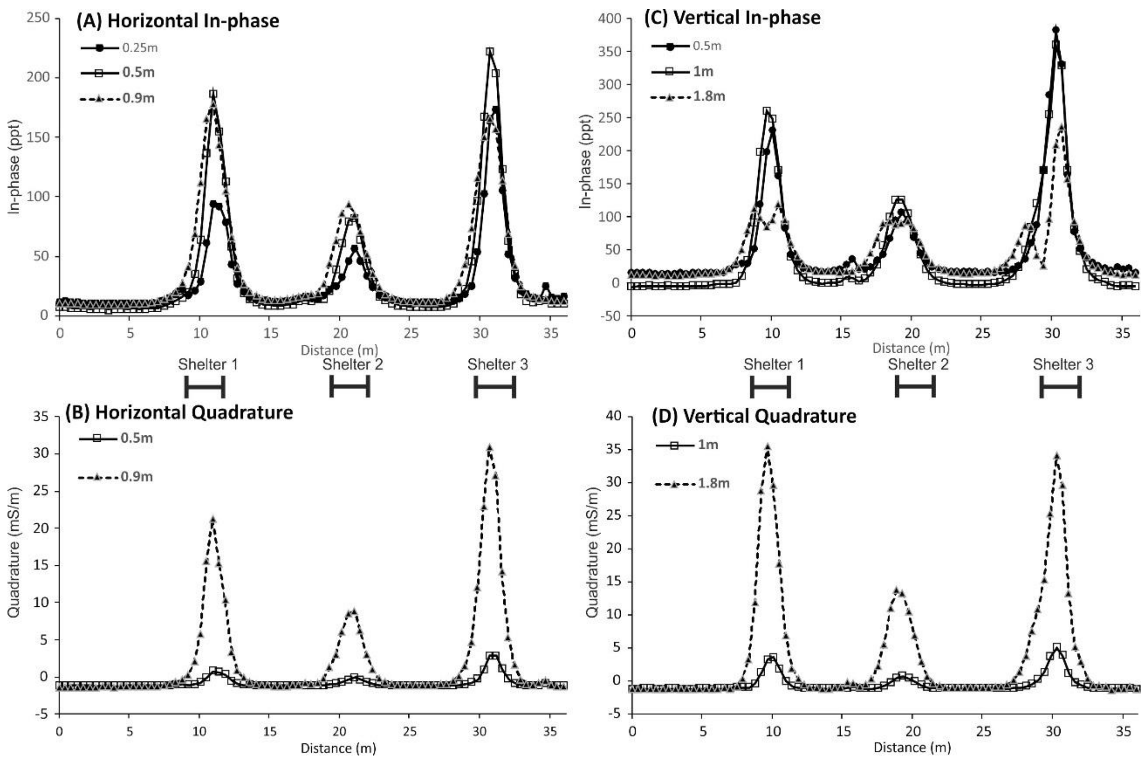

Figure 8. EM survey processed data results, showing respective Horizontal (A/B) and Vertical (C/D) Orientated dipole configurations, in-phase and quadrature datasets over the survey line (Fig. 5). The CMD Mini-Explorer also allows effective different penetration depths to be collected (see respective keys) acquired over the survey line, with the location of the three Stanton-type air-raid shelter positions marked.

Bulk-Ground Electrical Resistivity Results

The CST data for both 1m and 1.5m probe spacing showed three relatively low resistivity anomalies (-40 Ω.m to -20 Ω.m) on the 2D profile, which could be correlated to the three air-raid shelters positions (Fig. 9). The ERI 2D profile shows three, relatively low apparent resistivity (~20 Ω.m) anomalies, compared to background values (~80+ Ω.m), which could be clearly correlated to the three air-raid shelter positions (Fig. 10).

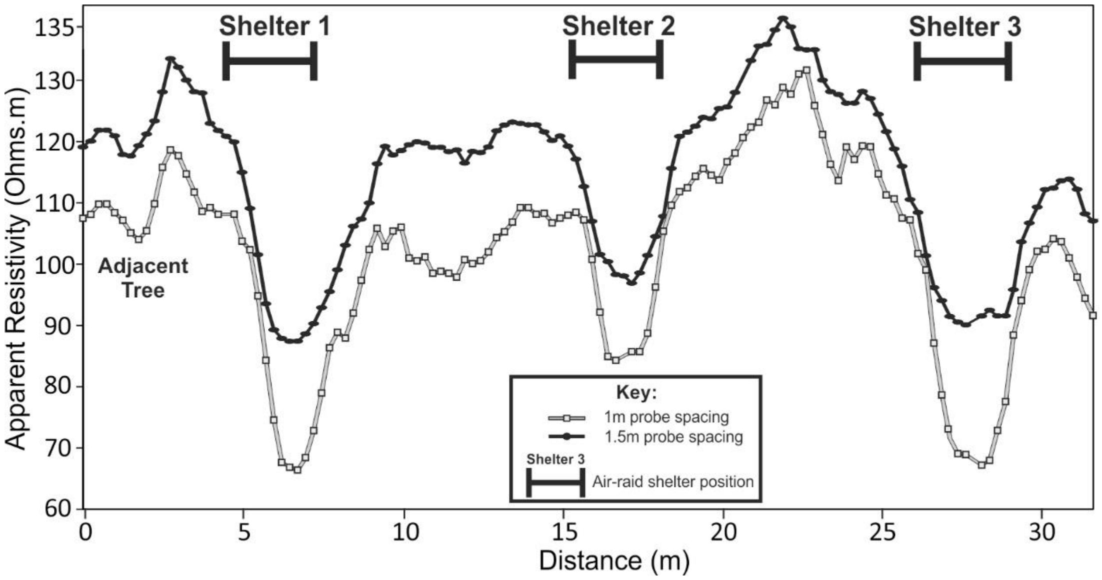

Figure 9. Bulk electrical resistivity survey processed data (both 1m and 1.5m spaced probes – see key) acquired over the survey line (Fig. 5), with the location of the three Stanton-type air-raid shelter positions marked and other pertinent features.

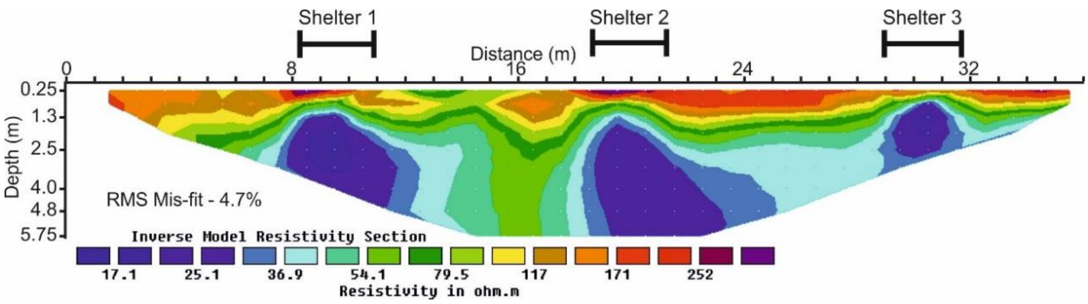

Figure 10. Inverted Electrical Resistivity Imaging (ERI) 2D profile results over the survey line (Fig. 5), using a logarithmic colour-contoured scale (see text), with the three Stanton-type air-raid shelter positions marked.

Micro-gravity Results

The processed residual Bouguer microgravity 2D profile showed two clear negative anomalies that could be correlated to the Shelter 1 and 2 positions. These were ~0.5 mGal lower than background readings and this was deemed to be significant, especially when compared to the repeat measurement variations. The survey line needed to be longer to image shelter 3, which was not possible due to restrictive terrain (Fig. 11).

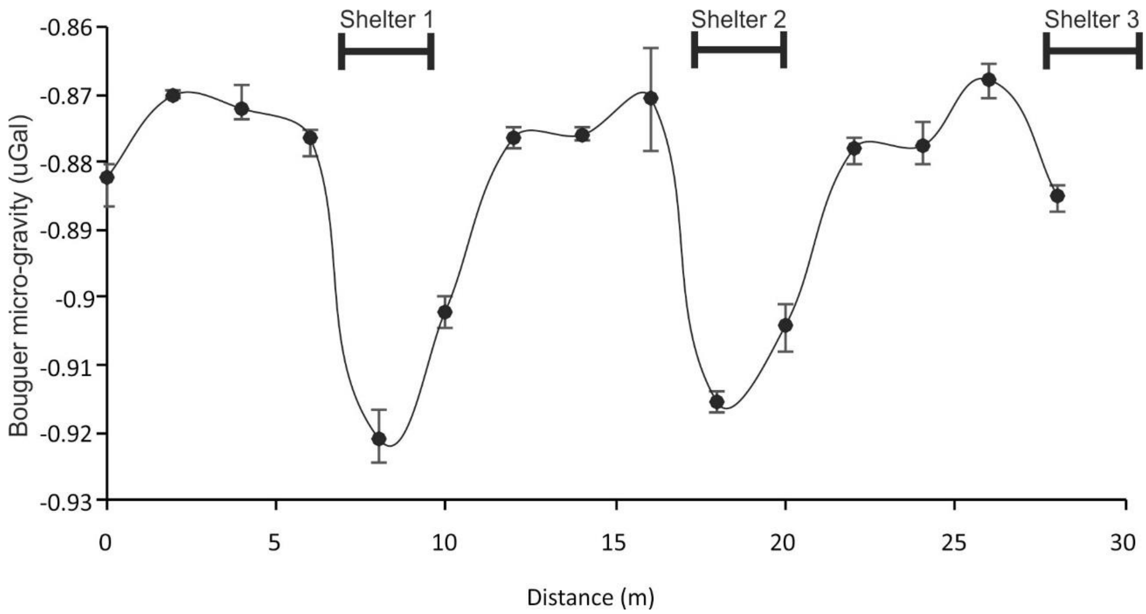

Figure 11. Micro-gravity processed results (with repeat measurement error bars shown) over the survey line (Fig. 5), with the three Stanton-type air-raid shelter positions marked.

Ground Investigations

The air-raid shelters were observed to be partially exposed on initial site investigations, so the three Stanton shelter dimensions (each 9m long, 2.3m wide) could be correlated with the geophysical data, as shown in the preceding sections.

A Handykam™ drain camera system was also used to inspect the interior of these shelters – the resulting footage was not good enough to include here, but did show voids within Shelters 1 and 3 with some collapsed artificial material present. Metal reinforcement bars were also observed within concrete in the roof and walls.

SITE 2: SHEPHERD'S BUSH COMMON, LONDON, UK

Shepherd's Bush Common in Central London had five public air-raid shelters constructed (Fig. 12), which are visible on aerial photographs taken in 1946 (Fig. 13a). These shelters therefore conformed to a type that were brick built and partially buried.

Since then, the common has not been developed (Fig. 13b), although surface landscaping works in 2011 had located the shelters within contaminated soil and back-filled them. Therefore, these shelters were expected to be in a poor state of preservation. The local geology of the site is a mixture of clay and sandy loam overlying Lower Eocene London Clay Formation bedrock.

An initial site investigation was undertaken in April 2017, finding trees, some ground vegetation cover and made-ground with debris. The air-raid shelters were not observed, in contrast to Site 1. A simple topographical survey was undertaken to map the modern site features and determine where the geophysical survey grid should be located (Fig. 12).

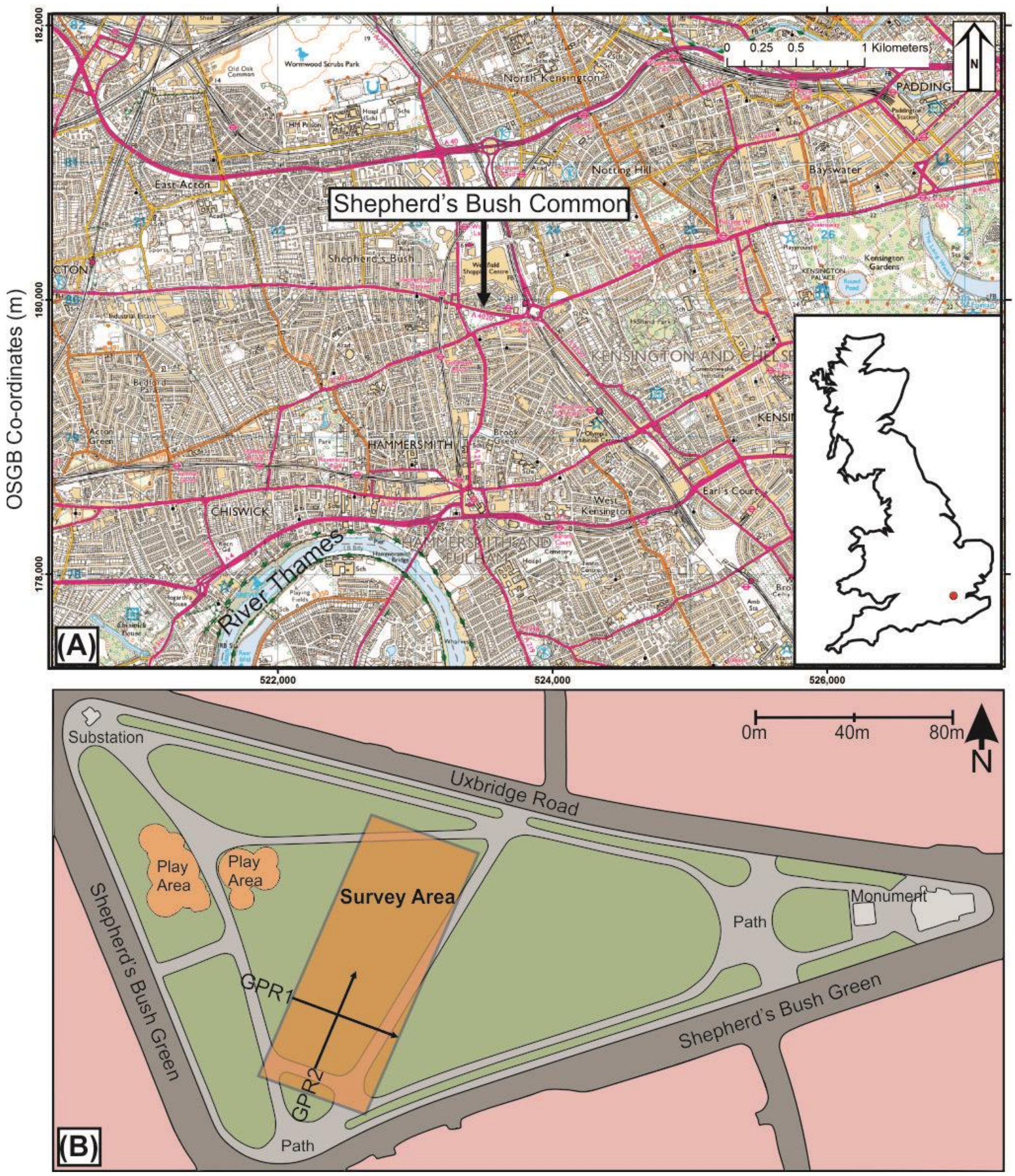

Figure 12. (A) Location map of Shepherd's Bush Common, London, with UK location (inset). Map courtesy of EDINA™ DigiMap (2016). (B) Shepherd's Bush Common study site 2 map, showing the geophysical survey area and the two GPR 2D profile locations shown in the paper.

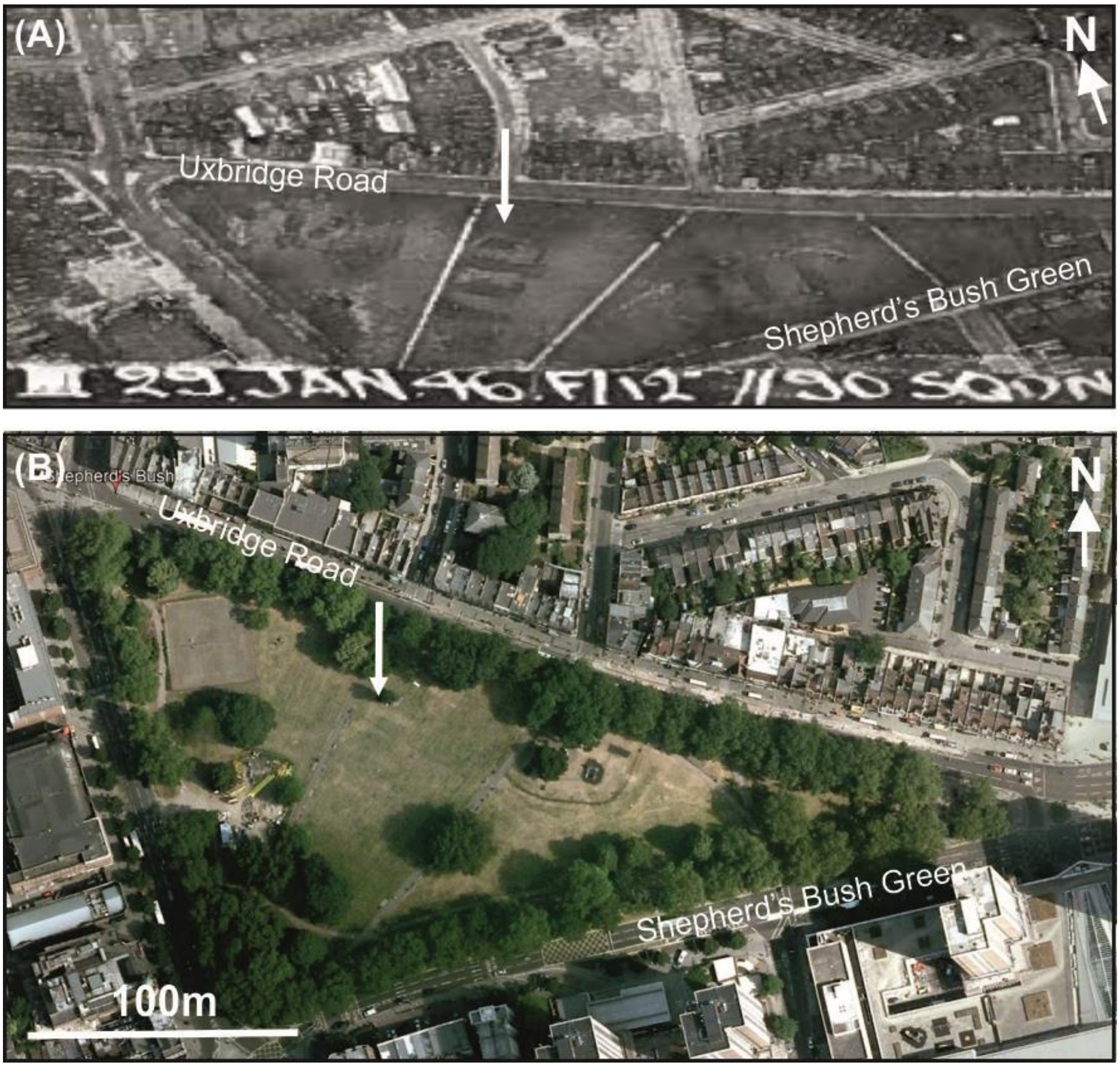

Figure 13. (A) 29/01/1946 aerial photograph of Shepherd's Bush common with five air-raid shelters still visible (arrow) (© of Hammersmith Borough Council) and (B) .

SITE 2: DATA ACQUISITION AND PROCESSING

A survey grid was set up over the presumed air-raid shelter positions (Fig. 12b), and GPR and EM surveys were undertaken.

Ground Penetrating Radar Survey

Following initial testing of the GSSI™ SIR-4000 system, a 400 MHz frequency, fixed-offset (0.16m) antenna was used to collect 2D profiles at 1m separation in both N-

S and E-W orientations with readings taken at 0.02 m intervals. Standard data processing steps were applied using GSSI RADAN v.7 software comprising time-zero to remove the air-gap, a user-defined gain-curve to compensate for signal attenuation, and a bandpass filter to eliminate the high and low frequency noise. Time-slices were generated in Sandmeier™ REFLEXW v.8.5 software using the standard processing steps given in Site 1.

Electro-Magnetics Survey

A Geonics™ EM61-MK2A conductivity meter was utilised, after being calibrated in a geophysically quiet area of the site, to collect VMD mode in-phase and quadrature data on the same survey grid. Standard data processing steps were applied, namely rectification of positions to OSGB co-ordinates, removal of spurious outlier data points and a digital contoured surface grid generated from sample points in Oasis™ Montaj v.7. software.

SITE 2 RESULTS

GPR Results

The 400 MHz frequency 2D GPR profiles possibly show the remains of two of the shelters approximately 0.5 m below ground level (Fig. 14). There was severe signal attenuation beyond 1 m depth, most likely due to either clay-rich soil and/or made-ground/rubble. The horizontal time-slice also did not clearly define the air-raid shelter positions, the results being dominated by path and memorial foundations (Fig. 15).

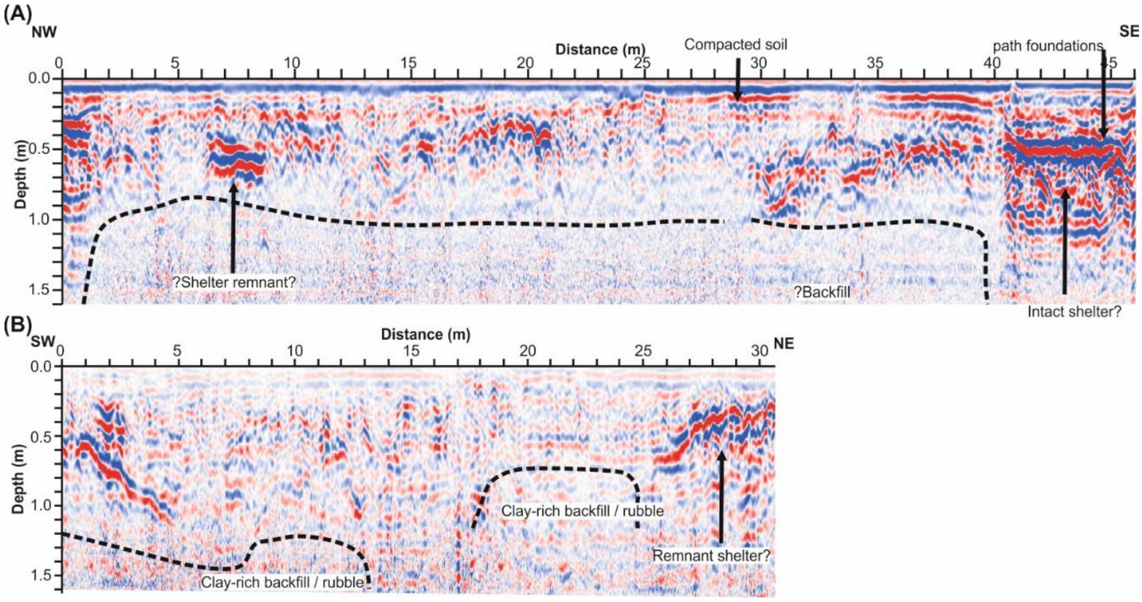

Figure 14. 400 MHz frequency GPR 2D processed profiles (A) GPR1 and (B) GPR 2 acquired over Shepherd's Bush Common (Fig. 12b for location), with interpretations of air-raid shelter positions and other pertinent features.

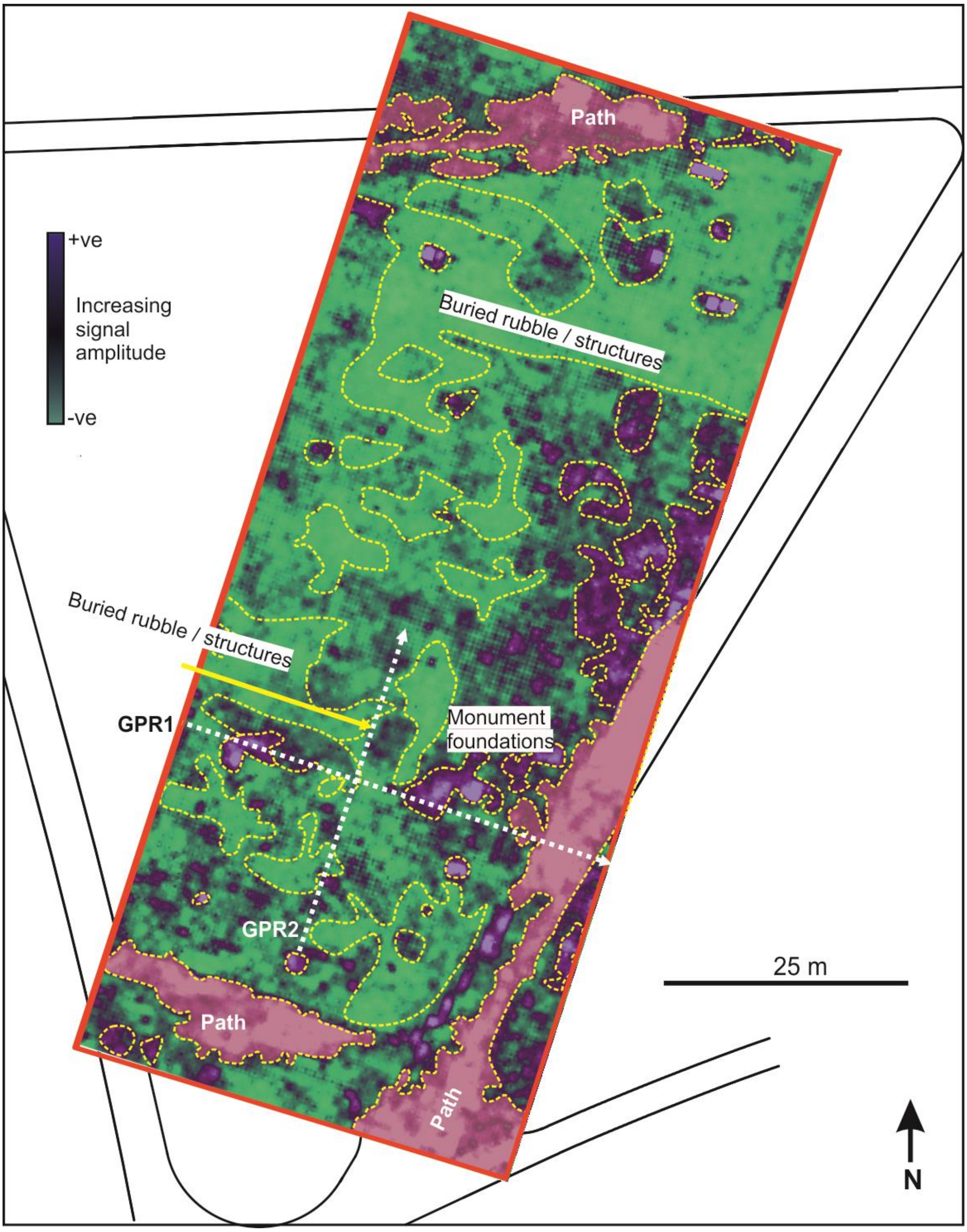

Figure 15. 400 MHz frequency GPR horizontal time slice at 0.5 m depth, generated from the 2D profiles, with the major interpreted features marked.

EM results

The EM61 results show clearly defined, linear, high-conductivity anomaly features present that could be the remains of reinforced concrete walls of the air-raid shelters (Fig. 16) suggesting that they were brick-built shelters. The more subtle linear high anomaly features in the south could be related to the shelters. Note there were also numerous other conductive isolated materials (Fig. 16).

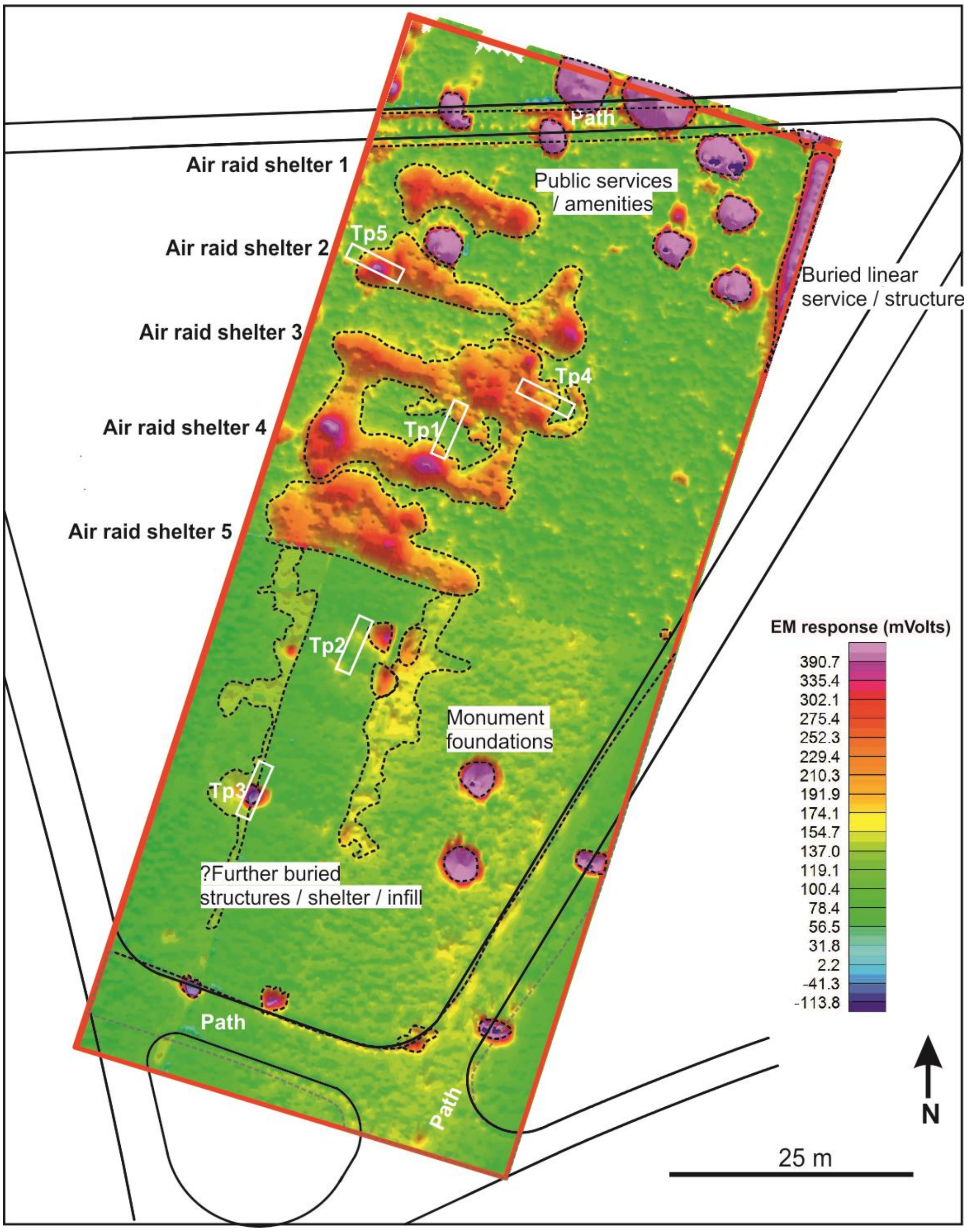

Figure 16. Electro-magnetic EM61 processed results (Fig. 12 for location) with pertinent features, including the five air-raid shelter remains and subsequent Trial Pit (TP 1-5) locations marked.

Ground investigations

Subsequently five trial pits were dug onsite to 1.2 m bgl which targeted the geophysical anomalies (see Fig. 16 for location). No below-ground voids were encountered, with loose fill comprised of numerous bricks, reinforced concrete (with one *in situ* in TP2) and a metal corrugated sheet found. These results suggest that the shelters had been demolished and backfilled with conductive waste material prior to the geophysical survey being conducted.

SITE 3: SOUTH LONDON, UK

A large reinforced concrete, public buried air-raid shelter was constructed in an area in inner city South London (Fig. 17), the precise location of which is withheld due to Council's wish to keep the site confidential. This is barely visible on wartime aerial photographs. The local geology of the site is clayey loam soil with up to 3 m of concrete, clinker and made-ground overlying the Lower Eocene London Clay Formation bedrock. The area is currently occupied by a series of post-WW2 council-estate buildings, landscaped grass areas and multiple carparks. A simple topographical survey was undertaken to map the modern site features and determine where the geophysical survey grid should be located (Fig. 17).

An initial site investigation was undertaken in May 2017, finding a flat grassed area, some utility service manhole covers and a presumed entrance to the below-ground shelter (Fig. 17).

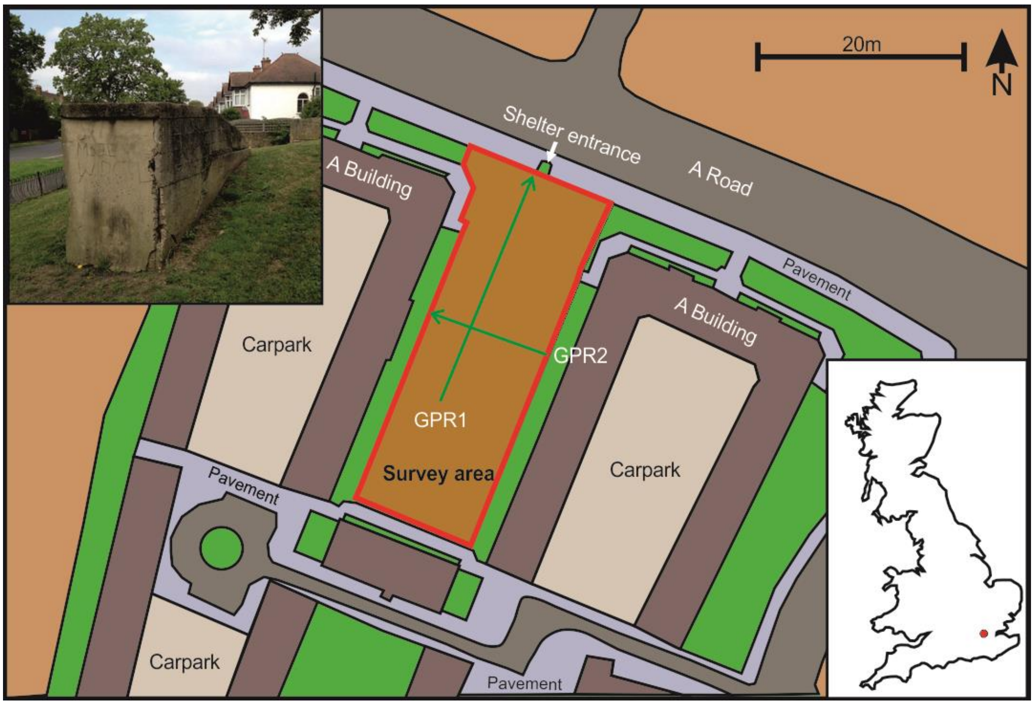

Figure 17. South London study site 3 map (location map inset), showing the geophysical survey area, the entrance (photograph inset) and the two GPR 2D profile locations shown in the paper. Map courtesy of EDINA™ DigiMap (2016).

SITE 3: DATA ACQUISITION AND PROCESSING

After a survey grid was set up over the presumed air-raid shelter positions (Fig. 17b), GPR and EM surveys were conducted.

Ground Penetrating Radar Survey

Following initial testing of the dual frequency GSSI™ 300/800 MHz Utility Scan system, a 300 MHz frequency, fixed-offset (0.16m) antenna was used to collect 2D profiles at 1 m separation in both NE-SW and NW-SE orientations. Trace spacings were 0.05 m. The time-zero, user-defined gain-curve and bandpass filter data processing steps were applied using GSSI RADAN v.7 software.

Electro-Magnetics Survey

A Geonics™ EM61-MM2A conductivity meter was also utilised, after being calibrated in a geophysically quiet area of the site, to collect VMD mode in-phase and quadrature data on the same survey grid. Positions were converted to OSGB co-ordinates, outlier data points removed and a contoured surface grid generated from sample points using Oasis™ Montaj v.7. software.

SITE 3 RESULTS

GPR Results

300 MHz frequency GPR profiles show some obvious isolated, high amplitude features which are interpreted as shelter walls (Fig. 18), with strong amplitude, horizontal reflection events (Fig. 18) just below the present ground surface, interpreted

to be the shelter roof. There were also low signal amplitudes below the interpreted air raid shelter roof that was correlated with the EM anomaly onsite.

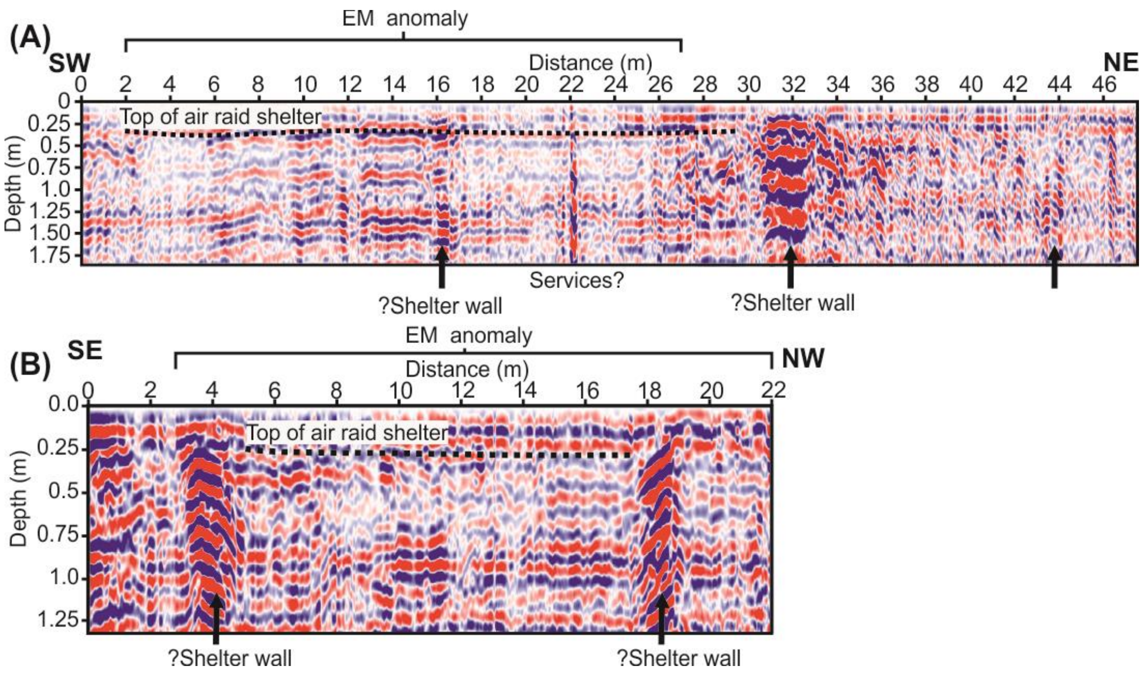

Figure 18. 300 MHz frequency GPR 2D processed profiles (A) GPR1 and (B) GPR 2 acquired over the South London study site 3 (Fig. 17 for location), with interpretations of air-raid shelter positions, EM anomaly and other pertinent features.

EM results

The EM61 produced a very clearly defined, rectangular, high-conductivity anomaly present in the central area that correlates with the public air-raid shelter roof (Fig. 19). Therefore, this suggests that the concrete roof will be comprised of conductive material. When combined with the GPR profile results, the shelter roof appeared to be still supported by walls (Fig. 18).

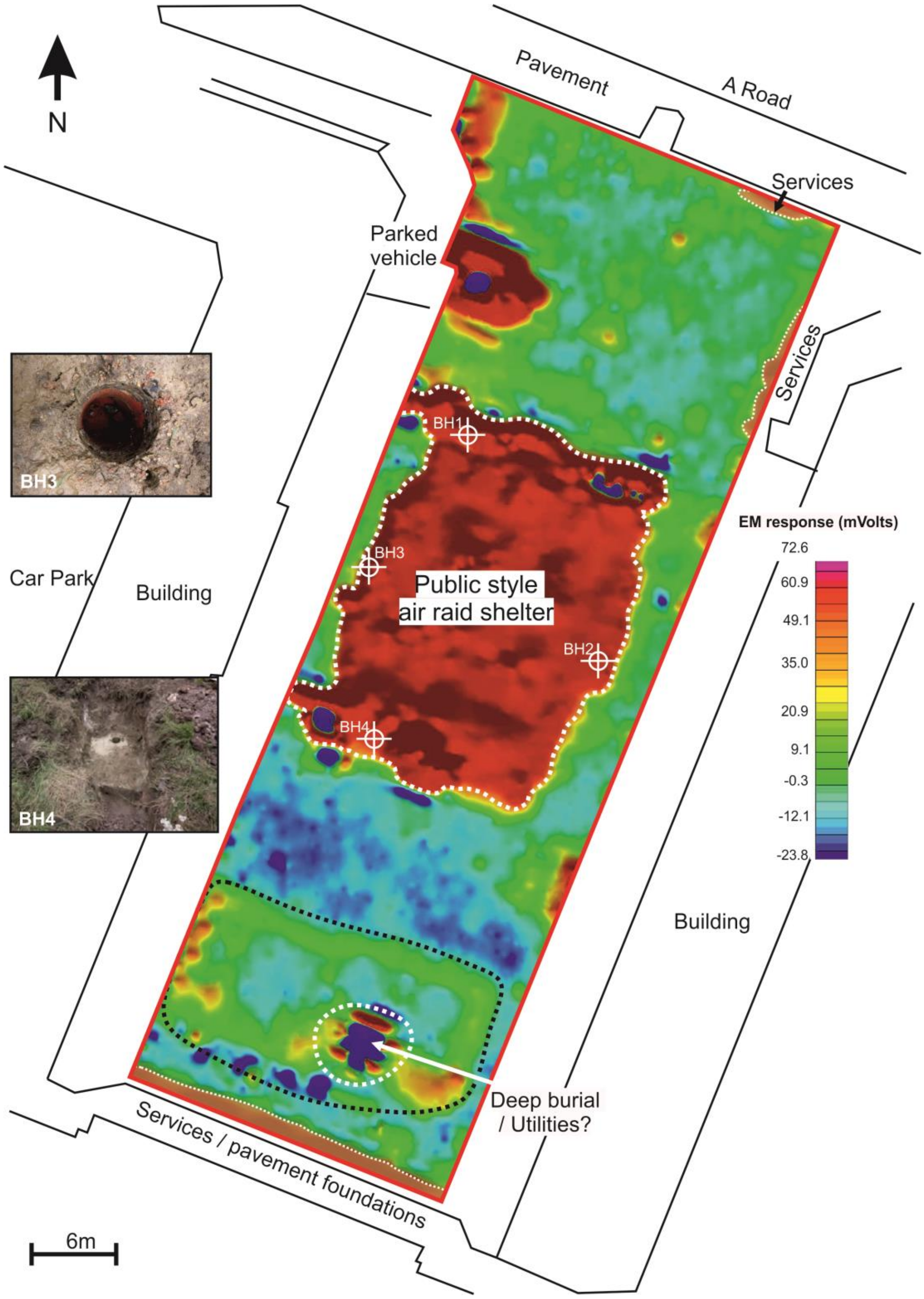

Figure 19. Electro-magnetic EM61 processed results (Fig. 17 for location) with pertinent features, including the below-ground public air-raid shelter remains and subsequent borehole positions (BH1-4) marked. Photographs of Boreholes 3 and 4 are also shown (inset).

Ground investigations

Four Targeted 150 mm drill cores were subsequently intrusively investigated onsite (see Fig. 19 for location). About 20 cm - 55 cm of topsoil and gravelly clay was present which overlaid ~20 cm layer of reinforced concrete that contained metal reinforcement bars. One core (BH3) had relatively poor condition concrete present with steel wire within it and a brick layer beneath (Fig. 19).

DISCUSSION

During WW2, aerial attacks (and coastal bombardment) on the British mainland contributed some 146,777 casualties, comprising 60,595 killed and 86,182 wounded (*Collier 1957*). In London alone, during the period of the 'Big Blitz' from 7 September 1940 to 16 May 1941, there were 85 major bombing raids contribution some 23,949 tons of high explosive (HE) (*Collier 1957, p. 528*), and during the whole of the war, 71,270 tons of HE bombs, flying-bombs and rockets were deployed against Britain (*O'Brien, 1955, p. 680*). The level and extent of casualties was far fewer than had been predicted (see *Fitzgibbon, 1970*), and this was in no small way a result of the Government's preparations for Civil Defence, and the provision of air raid shelters (see *O'Brien, 1955*). As discussed, and identified in Table 2, there is a diversity of shelter types (see *Thomas, 2016*). With 'Dispersal' the dominant policy, there was reliance on the hardy 'Anderson' constructed in domestic gardens, surface brick-built shelters, or trenches. While it is understood that those deep shelters that were known to have been constructed with Government sanction – such as the tube extensions that were dug between 1942-44 – the majority of subsurface shelter types are relatively shallow. This has meant that the archaeological record of such shelter types is ill defined, and therefore in need of detection through geophysical prospection, backed up by traditional techniques.

Historical aerial photographs have proved particularly useful, for example at Abbey Hulton (Site 1) and Shepherd's Bush Common (Site 2), as other modern investigations of historical sites have shown (see, for examples, *Doyle et al. 2013*; *Pringle et al. 2007*). The Abbey Hulton site has been recognised by Historic England as historically important, albeit for the nearby medieval Hulton Abbey ruins; therefore, has not been recently developed. In contrast, the London site 3 had poor aerial photographs and both London sites did not have adequate site information of their respective air-raid shelters with respect to original construction and dimensions. The inconsistency around the available historical information may be related to the era, as rapid construction and development of these structures was the priority, especially during 1939-1940.

This paper also evidences that non-invasive, surface geophysical methods could be successfully used to not only locate WW2 air-raid shelters, but also to characterize their dimensions and materials, which mirrors other researchers' findings on wartime structures (e.g. *Everett et al. 2006*; *Pringle et al. 2007; Rees-Hughes et al. 2016*). Geophysical survey results also showed contrasts between shelters at the same site. For example, microgravity and magnetic gradiometry showed different responses for the three air-raid shelters at Abbey Hulton (Site 1). The large magnetic and EM conductive anomalies evidence the concrete construction was metallic which was subsequently confirmed by intrusive site investigions. Where air-raid shelters were filled in/partially destroyed at Shepherd's Bush Common (Site 2), some techniques were less useful (e.g. GPR) but EM survey results still delineated their location and approximate dimensions. The South London study (Site 3) also managed to locate the mass public shelter, chiefly due to the reinforced concrete roof through EM (confirmed through intrusive investigation), but also the supporting wall locations were successfully imaged by GPR.

Optimal survey type(s) and equipment configuration(s) did vary between the three study sites. The surveys at Abbey Hulton (Site 1) of the Stanton shelters showed that all the utilised geophysical methods were successful at locating the shelters, but the lower frequency (250 MHz) GPR frequency antenna was optimal due to fewer non-target anomalies being imaged and good penetration depths being achieved. In contrast at Shepherd's Bush Common (Site 2), GPR results were not successful, with EM61 judged optimal there. For the South London study (Site 3), EM was judged to be optimal but GPR results were useful to locate the vertically-orientated features such as supporting walls. Electrical resistivity survey equipment was judged to be optimally set up with a dipole-dipole 1.5 m probe separation at Abbey Hulton (Site 1), which was larger than the typical 0.5 m probe configuration for shallow level investigations (see *Milsom & Eriksen, 2011; Dick et al. 2015*). Gravity surveys would be useful to collect to determine if located shelters were filled or open. Finally, bulk ground conductivity surveys were found to be optimal at both London study sites 2 and 3, with the best definition of target anomalies.

The case studies allow an idealized workflow to be generated for geophysical surveying over suspected air-raid shelters. Case study 1 at Abbey Hulton evidenced that all the geophysical techniques applied could detect the presence of the air-raid shelters. Using multiple geophysical techniques helps to determine a variety of different physical properties from anomalies, which is typically the best approach. However, potential clients for geophysical surveys, generally, do not have the budget or will to pay or wait for the results from multiple surveys, which is the reason why the commercial surveys in London (Cases 2 and 3) only used GPR and EM. In order to establish a workflow for geophysical surveys over air-raid shelters, it is first required to establish the requirements of a potential client. The most common problem is that the presence of an air-raid shelter is suspected but its location is unknown or uncertain. As all the techniques can detect the shelter, an informed decision about which geophysical technique(s) should be applied at a specific site to delineate the position of a shelter. Both magnetometry and EM techniques permit rapid surveying to generate a 2D anomaly map; however, if the structure is concrete-only, a magnetic survey may fail to detect the target all together, whereas the concrete-only structure should produce a (negative) conductivity anomaly. Conversely, if there is a metallic structure, then the magnetic signature may be difficult to interpret in terms of the precise position of the shelter edges (see Fig. 7), whereas an EM survey should produce a relatively simple (positive) conductivity anomaly (e.g. Fig. 19). Therefore, the optimum technique for determining the position and composition of the shelter is an EM survey. However, the aforementioned techniques may be hampered by objects on, or very near, the surface (e.g. buildings, park benches, vehicles, power cables), by either obstructing data collection or creating anomalous data, masking the target of interest, and cannot collect data at depth. Therefore, another technique, such as GPR (with a shielded antenna) may be employed to investigate a potential air raid shelter without these external factors causing issues, and identify the structure location at depth.

If the depth to the top of the structure is required, then the two most useful surveys are GPR and ERI resistivity. Although the CMD Mini-explorer allows for different EM penetration depths, these are all relatively shallow. GPR surveys are more rapid and easier to calibrate than ERI that makes GPR the preferred technique here (e.g. Fig. 18). However, if the target is deep and/or in a radar absorbing material (e.g. clay), ERI may be required as a complementary technique. If ground engineering work is anticipated, then the presence of subsurface voids may be a concern. These may be detected with GPR or ERI methods, but a ‘void or indeed loosely-filled material is best located and assessed by using microgravity (e.g. Fig. 11 and see *Tuckwell et al. 2008*). However, ERT may be required if the voids are too small and/or deep to generate a gravity anomaly above the detection threshold determined by the desk study. This discussion leads to the idealised workflow shown in Fig. 20, suggesting the optimum survey techniques for location and depth determination of buried air-raid shelters, and the detection of potential voids associated with them.

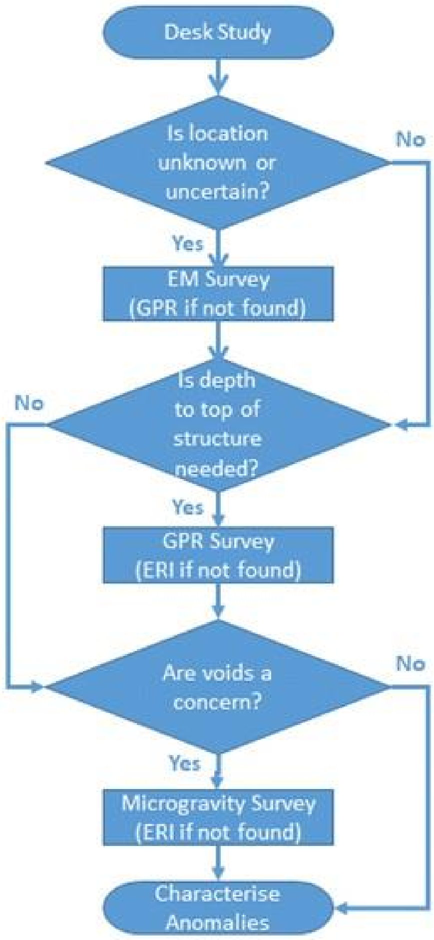

Figure 20. Suggested workflow for geophysical surveys over suspected buried air-raid shelters.

CONCLUSIONS

This paper presents results of non-invasive geophysical surveys of WW2 air-raid shelters in three different locations in the UK, one in Stoke-on-Trent and the other two in London. Given the diversity of air raid shelter design and deployment, it provides means of determining such sites that remain in the urban environment.

A desktop study found the Abbey Hulton study (Site 1) to have three Stanton-type air-raid shelters to be still visible from aerial photographs in 1974. The Central London study sites had five separate brick-built air-raid shelters shown on a 1946 aerial photograph (Site 2) and there was little information on a larger below-ground public shelter at the South London site (Site 3).

Fieldwork collected GPR, magnetic gradiometry, electro-magnetics, bulk electrical resistivity (CST and ERI) and microgravity surveys over site 1, and GPR and electro-magnetics data over sites 2 and 3 in London. All techniques utilised could detect the shelters in site 1, with EM deemed optimal for sites 2 and 3 and low-frequency GPR surveys useful to narrow down shelter positions/walls on follow-up investigations.

Subsequent site investigations confirmed the results at all three study sites, the Stanton air-raid shelters at study site 1 were partially filled, the brick shelters at site 2 were completely refilled with conductive material and the public below-ground shelters at site 3 were still intact.

Further work should geophysical survey other air-raid shelters, ideally an Anderson shelter which have not been surveyed in this study, to give the spectrum of common WW2 air-raid shelters.

This study has shown how modern non-invasive geophysical techniques can provide new knowledge on WW2 air-raid shelters in the UK with a suggested workflow generated to assist other researchers to locate and characterize them.

GEOLOCATION INFORMATION

The Abbey Hulton study site 1 has the following co-ordinates: 53º02’22”N, 2º08’33”W. The Shepherd’s Bush Common study site 2 has the following co-ordinates: 51º30’14.4”N, 0º13’22.4”W. The study site 3 location has been anonymised due to client commercial sensitivities.

ACKNOWLEDGEMENTS

Stoke-on-Trent Council are thanked for allowing site access at Abbey Hulton, as are Historic England for permitting non-intrusive investigations within the Scheduled area, in accordance with Ancient Monuments and Archaeological Areas Act (1979). Kensington and Chelsea and London Metropolitan Borough Councils are thanked for permission to publish data from sites 2 and 3 respectively. Norman Bell of Allied Associates Ltd. is thanked for the loan of the GF Instruments™ CMD mini-explorer for this project. Michael Roberts, Nicholas Cooper and James Francis are acknowledged for data collection assistance. Steve Hunnisett provided the image of the extant surface shelter. Dr Mike Still of Dartford Borough Museum kindly provided information on Dartford Air Raid Shelters.

FUNDING DETAILS

No funding has been obtained for this study.

DISCLOSURE STATEMENT

There is no financial interest or benefit that has arisen from the direct applications of this research.

BIOGRAPHICAL NOTE

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Jamie K. Pringle is a Senior Lecturer in Geosciences at Keele University, having held previous positions at Liverpool University and Reynolds Geo-Science Ltd. Jamie has worked on various military and historical scientific investigations, the most high profile being a site investigation of the 'Great Escape' of WW2 Allied P.O.W.s in 1944 in Sagan, Western Poland.

Peter Doyle is Visiting Professor at London South Bank University, Secretary of the All Party Parliamentary War Heritage Group and is a geologist specialising in battlefield terrain from the late nineteenth century onwards. A regular contributor to TV documentaries, Peter was also a visiting lecturer on military geology at the United States Military Academy, West Point, in 2007 and 2014. His many contributions include multidisciplinary studies of trenches, terrain and military tunnels of both world wars.

Matt Stringfellow is an Associate Geophysical Engineer at RSK Environment Ltd. and a Chartered Geologist. He holds a MSci Hons. Degree in Astrophysics and Geology from Keele University (2003) with over 10 years experience on near-surface geophysical surveys.

Daniel Roberts is a Research Fellow and a PhD student at the School of Civil Engineering at the University of Birmingham. He obtained a BSc (Hons) in Geology and Physical Geography at Keele University (2013), an MSc in Geoscience Research Training at Keele University (2015), an MRes in Translational Quantum Technology at the University of Birmingham and is studying for a PhD in the application of Quantum Technology gravity for the Civil Engineering industry. Daniel is an experienced near-surface geophysicist, and his research interests lie in the use of geophysics for the Civil Engineering industry and wanting to create Open Source geophysical processing software.

Kris Wisniewski is a Teaching Fellow at Keele University, having a PhD in Forensic Science, and is an experienced site investigator in various forensic and archaeological investigations.

Ian Stimpson is a Senior Lecturer in Geophysics at Keele University, having held previous positions at Cardiff University and at the UK Blacknest Atomic Weapons Establishment. Ian has worked on geophysical-related research for over 30 years, on everything from studying local Staffordshire earthquakes microearthquakes caused by tunnelling, salt mine collapse and oil extraction. He has also studied the vibration of wind turbines and geoconservation.

Jon Goodwin is Senior Planning Officer (Archaeology/HER) at Stoke-on-Trent Council, working on various archaeology-related activities for at least 20 years.

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