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Abstract: There are various techniques available for forensic search teams to employ to successfully detect a buried object. Near-surface geophysical search methods have been dominated by ground penetrating radar but recently other techniques, such as electrical resistivity, have become more common. This paper discusses magnetic susceptibility as a simple surface search tool illustrated by various research studies. These suggest magnetic susceptibility to be a relatively low cost, quick and effective tool, compared to other geophysical methods, to determine disturbed ground above buried objects and burnt surface remains in a variety of soil types. Further research should collect datasets over objects of known burial ages for comparison purposes and used in forensic search cases to validate the technique.

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Title Page (with authors and addresses)

The use of magnetic susceptibility as a forensic search tool

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Graphical Abstract (for review)

Highlights:

- Magnetic susceptibility an under-utilised forensic search tool
- Relatively low cost, simple and quick to collect surface data
- Variety of test studies show measurable contrast over target versus background
- Use in active forensic case next stage

ABSTRACT

There are various techniques available for forensic search teams to employ to successfully detect a buried object. Near-surface geophysical search methods have been dominated by ground penetrating radar but recently other techniques, such as electrical resistivity, have become more common. This paper discusses magnetic susceptibility as a simple surface search tool illustrated by various research studies. These suggest magnetic susceptibility to be a relatively low cost, quick and effective tool, compared to other geophysical methods, to determine disturbed ground above buried objects and burnt surface remains in a variety of soil types. Further research should collect datasets over objects of known burial ages for comparison purposes and used in forensic search cases to validate the technique.

Keywords; forensic science; forensic geophysics; search; magnetic susceptibility

1. Introduction

For a successful criminal conviction to occur, it is often essential to locate forensically important evidence [1]. The forensic objects being searched for vary from illegally buried weapons [2-3] and explosives [4], landmines and improvised explosive devices or IEDs [5], drugs and weapons caches [6] to clandestine graves of murder victims [7] and mass genocide graves [8]. In such situations, burials are usually shallow, less than 3 m below ground level or bgl [9-10]. In addition, the disposal of toxic waste in illegal dumps is a significant and growing issue [11-12]. Water-based forensic geoscience surveys have also been undertaken to assist police and environmental divers, especially in water with poor visibility or large search areas, see [13-16].

Forensic search methods vary widely, for example, in the UK a search strategist is usually involved in a case at an early stage to decide upon the highest probability of search success [17], whereas in other countries a search may not be methodical, investigations may not be standardised and a variety of techniques are undertaken, depending upon local experience [18]. [19] also detail how illegal disposal of waste has to be detected and characterized, before a criminal charge can be brought, with US environmental crime investigation approaches detailed in [20]. Metal detector search teams [21] and specially trained search dogs [22-23] are both commonly used during either initial investigations or as part of a phased sequential programme.

Geoscientific methods are being increasingly utilised and reported upon by forensic search teams for the detection and location of clandestinely buried material [1]. These generally start from the large-scale remote sensing methods [24-26], aerial and ultraviolet photography [9,27], thermal imaging [28], to ground-based observations of vegetation changes [29], surface geomorphology changes [30], soil type [17] and depositional environment(s) [27], near-surface geophysics [1], diggability surveys [17] and probing of anomalous areas [31-32] before topsoil removal [29] and finally controlled excavation and recovery [9].

Near-surface geophysical methods rely on there being a detectable physical contrast between the target and the background (or host) materials (see [33]). Although geophysical methods for forensic search are dominated by ground penetrating radar or GPR [1], a multi-method phased approach is suggested as best practise and is reviewed in [1]. For example, both Electro-Magnetics or EM [34] and its reciprocal electrical resistivity [35] techniques are relatively fast to acquire and resulting anomalous areas can then be further investigated by higher resolution methods. GPR has also been shown to not be optimal in certain search environments, for example in wooded environments [34], water-logged [36], saline-rich [37], clay-rich [38] and heterogeneous [39] soil types, these soil types significantly attenuating radar signal amplitudes. Metal detectors are actually active EM methods relying on metallic objects being good conductors and transmitting their own secondary EM field in response to the instruments' primary EM field (see [3,6]), whereas magnetic methods are passive measurements which measure variations in the Earth's magnetic field due to nearby objects [33,40]. Magnetic surveys have proved not to be optimal in forensic (e.g. [8,41]) and control search studies [42], as they commonly suffer interference from both above- and below-ground non-target objects [33].

All substance have magnetic properties and, when a magnetic field is applied to soil and rock, the degree of magnetization can be measured as the magnetic susceptibility or MS in SI dimensionless units [43]. MS causes are complex and are a combination of dia-, para- and ferro/ferri-magnetism (see [33] for more information). There are wide variations in measured MS reported between different rock and soil types (e.g. [44]) with the largest values being partly attributable to the relative proportions of magnetic minerals present in the material. In soils, the presence of the ferrimagnetic mineral maghemite (Fe_2O_3, γ-Fe_2O_3) has a dominant effect on the magnetic susceptibility and is a low-temperature, oxidisation weathering product of the strongly magnetic minerals magnetite and titanomagnetite [45]. MS has therefore been used for site soil characterisation (e.g. [46]), forensic trace evidence (e.g. see [47-49]) and environmental forensic pollution studies [50-54].

Magnetic susceptibility surface surveys have also been used for quality control checking of magnetic surveys (see [39]), but they have not been used as a forensic search technique to-date, presumably due to their stated 6 cm penetration below ground level or bgl, although this is a function of effective response of the proportion of magnetic materials present [55-56]. MS has been shown to have poorly resolved a simulated clandestine grave in an urban depositional environment [39]. They are, however, commonly used in archaeological searches (e.g. see [46,57-58]), and have been shown to successfully locate areas of historic surface burning as the weakly magnetic iron oxide minerals in the soil (e.g. hematite and goethite) are transformed into the highly magnetic minerals magnetite and maghemite through heating/burning (e.g. [59-61]). This paper aims to validate the potential usefulness of magnetic susceptibility surface surveys as a forensic search technique through the use of seven illustrative forensic research studies with varying targets and post-burial ages, soil types and depositional environments. Three of these have been previously published but will allow a more wide ranging view of the technique in different forensic search scenarios. It will also be briefly compared to other, more commonly utilised forensic geophysics techniques and finally suggest best practise for such MS surveys.

2. Case studies

2.1 Magnetic Susceptibility equipment surface survey test

In order to confirm the magnetic susceptibility (MS) technique for sample measurement repeatability and reliability, a simple test was devised using a Bartington™ MS2D meter with 0.3 m diameter surface probe that costs ~£3,000, weighs 1.9 Kg and was connected to a ruggedised PC laptop with Bartsoft™ v.4 data acquisition software. Two relatively homogeneous rock Granite blocks had 4 and 6 sample positions, respectively, repeatedly measured for their magnetic susceptibility (Fig. 1a). Each sample position was measured ten times for its MS at 1 s duration, with the instrument being zeroed between each sample position. The MS survey process was also repeated at 09:00, 13:00 and 17:00 over one day. The local air temperature varied between 16 °C – 18 °C over the survey period.

The MS meter sample position repeatability was very good between surveys (Fig. 1b), with an average and maximum sample position repeat measurement difference of 11.3×10^{-6} and 19.9×10^{-6} respectively. The MS measured data reliability at each sample position was also very good, with SD average survey values of 7×10^{-6}, 1×10^{-6} and 2×10^{-6} for the three respective surveys. The minor sample measurement variations between repeat surveys were thought to primarily be due to slightly different sample positions although this was deliberately kept to a minimum. This test therefore gave confidence in MS equipment operation and sample measurement repeatability and reliability.

2.2 Hole surface survey monitoring test

A field monitoring surface study was undertaken to quantify if the MS technique could be used both to detect disturbed ground and to determine if measured values changed over a one-year study period when compared to background measurements. This should prove if this method detects disturbed ground when no forensic object is present and if this is measureable over one year post-disturbance. A 1 m long survey line was therefore permanently marked by plastic pegs on a quiet semi-rural depositional environment of Keele University campus (Fig. 2a). A 0.2 m by 0.2 m sized hole ~0.1 m deep into the sand loam soil was created ~0.4 m - ~0.6 m along the survey profile, with the excavated grassed earth sod rotated 180° and carefully replaced in the hole. A Bartington™ MS2D meter with a 0.3 m diameter surface probe repeatedly collected magnetic susceptibility measurements every 0.1 m along the 2D profile. Each sample position was measured six times for its MS at 1 s duration, with the instrument being zeroed every five sample positions. The 2D profile was also MS surveyed using the same parameters before the disturbance to act as control. This control line average MS measurement was 637 x 10^{-6} SI with a 35 x 10^{-6} SD, typical MS values for those of a sandy loam brown earth soil that was present here (see Dearing et al. 1996). Average monthly site temperatures were 8 °C and the monthly rainfall average was 77 mm over the survey period.

MS results throughout the survey period showed anomalously high measurements over the area of disturbed ground compared to background values (Fig. 2b). The MS anomaly size was wider than the 0.2 m wide disturbance area; this was to be expected as the 0.3m diameter surface probe would measure part of the disturbance on sampling positions adjacent to the 0.4

m – 0.6 m wide disturbance area. Although there was variation of measurements between surveys, the relative positive anomaly was consistently present, both in its position along the profile and in amplitude (averaging +92 x 10^{-6} SI) when compared to background values. Average MS readings also declined by the later surveys compared to early surveys (*cf.* Fig. 2b). This study gives some confidence that the technique works to consistently detect an area of disturbance in heterogeneous soil over a one year time period in a typically varied temperate climate.

2.3 Burnt clothes surface survey test

A field study was undertaken to quantify if the MS technique could be used to detect a site of burnt clothes left on the ground surface, the same target under overturned soil and finally once they have been removed. A 5 m long survey line was therefore again marked in a quiet semi-rural depositional environment of Keele University campus. Two cotton T-shirts (Fig. 3a) and jogging trousers (Fig. 3b) were carefully burnt using 0.5 L of domestic kerosene within brick-contained 0.5 m x 0.5 m areas (Fig. 3c) along the profile, before one was overturned into the underlying soil (Fig. 3d). The bricks were present to stop any potential ash contamination from spreading during burning but were subsequently removed. The profile was MS surveyed by a Bartington™ MS1 meter with a 0.3 m diameter surface probe every 0.25 m along the 2D profile, before the surface clothes were scraped clear by a metallic spade before being re-surveyed.

MS results showed significant variability between surveys; the highest anomaly (~2.5 times that of relative background values) was surprisingly that of the burnt clothes underneath the overturned soil; the next highest anomaly (~2 times) was the burnt clothes left on the surface and the final MS survey with the ash scraped clear was difficult to differentiate from that of background values (Fig. 3e).

2.4 Buried weapons case study

A field study was undertaken to determine if the MS technique could detect simulated forensic buried objects in a semi-rural environment on Keele University campus, U.K. This had the same soil type as the two previously described case studies. Simulated forensic objects included a replica Colt 0.45 calibre handgun, domestic stainless steel kitchen breadknives, a UK metallic mortar ammunition box and decommissioned WW1 and WW2 allied hand grenades (see Fig. 4a and [2] for information). Objects were buried ~0.15 m below the ground surface in a non-ordered configuration before the excavated material was then used to re-fill each hand-dug hole back to ground level. Multi-geophysical methods were utilised to establish optimum search detection techniques over both grass and domestic patio environments, as well as creating a suite of datasets for search teams to utilise and compare their datasets to in such forensic search areas. A Bartington™ MS1 meter with a 0.3 m diameter surface probe collected magnetic susceptibility measurements every 0.25 m along 0.25 m spaced 2D profiles over a 5 m by 5 m surface area before burial, after burial (Fig. 4a) and again after the domestic patio was laid (Fig. 4b). MS measurements were then despiked to remove isolated anomalous values, de-trending to remove long-wavelength site trends and a minimum curvature algorithm used to create a digital gridded surface. The site was also surveyed by other near-surface instruments for comparison [2].

MS surveys were successful in detecting the buried objects in both the grass and domestic burial scenarios (cf. Fig. 4d-e), only the control objects (1-2) were not resolved in the grass survey although note the handgun (9) was poorly resolved during both post-burial surveys. It was also interesting to note the relative MS contrasts of target against background values were much higher (~5 times) for the grass scenario compared to (~twice) for the domestic patio scenario but both were detectable.

2.5 Urban simulated clandestine grave case study

A field study was undertaken to determine if the MS technique could detect a simulated clandestine burial in an urban environment on Staffordshire University campus, U.K. This had a dominantly 'made-ground' clay-rich soil type. The simulated clandestine grave was hand-dug to 0.6 m bgl before a clothed plastic resin skeleton with animal soft tissue and 4.5 L of salt solution added before reburial with the excavated material back to ground level (see Fig. 5a and [39] for information). Multi-geophysical methods were then used to establish optimum search techniques, one of these being a Bartington™ MS1 meter with a 0.3 m diameter surface probe, collecting magnetic susceptibility measurements every 0.5 m along 0.5 m spaced 2D profiles over a 6 m by 5 m surface area. MS measurements were then despiked to remove isolated anomalous values and a minimum curvature algorithm used to create a digital gridded surface.

The MS survey was not that successful at resolving the simulated clandestine grave (Fig. 5b), whilst relatively high values (~1.5 times) were measured over the target, compared to background values, there were also at least 4 other positions having similar MS measured values. This study therefore gave less confidence that this technique would be useful in such urban depositional environments.

2.6 Coastal simulated clandestine grave case study

A field study was undertaken in a coastal depositional environment in north-west England, U.K. Simulated clandestine graves of murder victims, using an adult-sized, metal-jointed fiberglass mannequin, were created in both sand dunes and on more organic-rich foreshore depositional environments (Fig. 6a/c). Both graves were hand-dug to a depth of 0.5 m and the excavated material was then used to re-fill the grave after the mannequin had been emplaced. Multi-geophysical methods were utilised to establish optimum search detection techniques as well as creating a suite of datasets for search teams to utilise and compare their datasets to in such forensic search areas (see [37] for information). A Bartington™ MS1 meter with a 0.3 m diameter surface probe collected magnetic susceptibility measurements every 0.25 m along respective 5 m long 2D profiles.

MS results from both sites show anomalously high MS measurements recorded over the clandestine graves relative to their background readings (*cf*. Fig. 6b/d) that were both low compared to typical homogeneous dry sand (~30-1000 SI x 10^{-6}) and organic-rich sediments respectively [40]. This is probably due to its salt-rich depositional environment reducing the

MS values. The anomalous readings over both graves were three times that of background readings. It was interesting to note that there was a significant MS measured anomaly over the sand dune simulated clandestine grave (see Fig. 6a), as both the grave contents and the surrounding materials were homogenous quartz sand grains. The wider MS anomaly measured over the foreshore simulated clandestine grave was thought to be dominantly caused by the organic-rich sediments from the grave left on the surface (see Fig. 6c).

2.7 19th Century unmarked grave case study

A geophysical survey was undertaken at St. John of Jerusalem Church in Hackney, London, UK, in order to locate the position of numerous unmarked burials in a graveyard that was closed in 1868. The soil type was a black seat earth. A trial MS survey was undertaken over a suspected grave position that was visually observed to have a rectangular topographic depression (Fig. 7a). A Bartington™ MS1 meter with a 0.3 m diameter surface probe collected magnetic susceptibility measurements every 0.25 m along 0.5 m survey lines within a 4 m by 4 m survey area. MS measurements were then despiked to remove isolated anomalous values, and a minimum curvature algorithm used to create a digital gridded surface.

MS results show anomalously high MS measurements recorded (~three times) over the suspected unmarked grave, compared to background values (Fig. 7b). The approximate anomaly size (~ 1.75 m x 1 m) is also what would be expected for an adult-sized burial in such a graveyard. Within the anomaly area itself two sampling positions are very high compared to all the other MS measurements at the site. It is now known if there was indeed a burial present here due to a lack of archaeological excavation.

2.8 Anglo-Saxon unmarked grave study case study

A near-surface geophysical survey was undertaken at RAF Lakenheath in East Anglia, UK, to determine the location of possible inhumations within an Anglo-Saxon grave following the removal of topsoil (see [62]). A Bartington™ MS2D meter with a 0.1 m diameter surface probe collected MS measurements every 0.1 m along 0.1 m survey lines across a 1.4 m by 2 m survey area identified from soil coloration. MS measurements were then despiked to remove isolated anomalous values, and a minimum curvature algorithm used to create a digital gridded surface (Fig. 8a).

Subsequent archaeological excavation found the isolated adult skeletal remains were in surprisingly good condition given the known acidic nature of the surrounding soils (Fig.8b); the archaeological recording of the recovered remains have been superimposed onto the MS dataset for comparison (Fig. 8a). Clearly there is a relatively good visual comparison recorded between relatively the relative high MS values (~5 times), compared to background values, with the subsequent excavated remains.

3. Discussion

The initial rock granite MS survey test clearly showed excellent repeatability and reliability of measured surface MS survey results in a relatively homogenous medium. The instrument used gives similar results to other MS meters shown by other authors (see [56]). There was also little measureable diurnal variation observed in recorded measurements, in contrast to other magnetic surface surveys, e.g. the proton precession and alkali vapour magnetometers, which do require diurnal correction during data processing to be undertaken (e.g. see [40,42]). The MS equipment also seemed to have little variation in re-acquired sample position measurements that was similarly observed to both electrical resistivity and GPR shielded antennae in other studies (e.g. [2]), most probably due to similar operational procedure of having direct contact with the ground; this both negates any potential variability of instrument height as experienced with typically utilised magnetic instruments and reduces potential above-ground sources of interference.

The field monitoring surface study of disturbed ground was informative; not only did it show a relatively consistent MS peak compared to background values even though no forensic object was emplaced, but that it was also still detectable up to a year after disturbance. This is important forensically, evidence of disturbed ground could be crucial to gain forensic trace evidence, as has been observed in Balkan Civil War primary and secondary clandestine grave depositions [63] and for landmine clearance operations [64]. Whilst areas of disturbed ground have been shown to be electrically detectable from background relative values due to a combination of increased soil porosity and hence water content [65] this does widely vary depending upon seasonality, moisture content, soil type and moisture content [66]; therefore the MS method looks to be more consistent and detectable over this time period which is promising.

The burnt clothes study was informative as it showed MS could be used to detect the position of such forensic targets which could be very important for criminal trace evidential purposes (see [67-68]). Other research has additionally shown that when organic matter in a soil burns at ~600-700 ^{0}C it can change the soil's weakly magnetic minerals to magnetite and maghemite on re-oxidation as the burn ceases, all of which further increase relative MS values ([46,69-70]). Mathematical calculations can also be undertaken from MS data to estimate the approximate historic fire temperature ([71]).

The buried weapons study was useful as these are commonly required by forensic search teams to locate for evidential purposes. Whilst metal detector and GPR are the commonly used geophysical techniques for such searches [1], the MS survey had the best detection success rates of all the techniques trialled [2]; this is important as excavating a domestic patio is obvious time consuming and costly (see [4]). MS surveys also give a numerical value for sample positions which is less usual in metal detectors. The domestic patio scenario also reduced the relative contrast of MS values above the forensic targets from five times to twice that of the background values but they were still detectable. It is also interesting to note that the MS survey was successful even though the target burial depth was deeper than the instruments' perceived penetration depth of 6cm; therefore suggesting the instrument was picking up the soil disturbance over the target rather than the target itself.

The urban simulated clandestine grave study was useful as, despite the MS survey not being that successful at delineating the search target, it provides valuable information on using the technique in common urban search scenarios (see [4]). It may be that MS is not an optimal search technique in such urban depositional environments due to the amount of disturbed ground that will be present and thus providing difficulty in differentiating from the target versus the background MS values.

The coastal simulated clandestine grave study was again found to successfully detect the target burial although this was ~0.5 m bgl (Fig. 5); it is suggested that the disturbance was again being detected. Whilst this would be expected on the foreshore scenario as there were a variety of organic-rich and quartz sand heterogeneous soil present, in the dune scenario the soil was comprised of relatively homogenous quartz sand grains and thus little material change would have been present here. The foreshore example shows one of the potential difficulties with this technique in detecting a buried object if the site has been recently disturbed; it would be very difficult to detect which area had the forensic target of interest present. The MS survey technique compared favourably to both GPR and resistivity in the sand dune scenario with it being much better on the foreshore as both the GPR and resistivity methods were poor in this depositional environment (see [37]).

The 19th Century unmarked grave study showed that forensic targets over 100 years old could be detectable using the MS method although subsequent archaeological excavations have not been undertaken; other authors have used depressions and geophysics to successfully detect unmarked burials (e.g. [72]) but other studies have found that suspect burial positions may not, in fact, be what was suspected [73]. Clearly more geophysical data over marked burials with known burial dates would assist in determining if MS could be a useful technique in this arena and, indeed how long they would be detectable for.

The historic unmarked grave study is very useful as it shows that MS can potentially still be used as a successful detection method even with a post-burial date of 1,000+ years. Unlike most of the other case studies, it is probably not disturbed soil that would be causing a measureable MS difference from background values. It has been suggested that it is both Iron loading from haemoglobin and the presence of magnetotactic bacteria, which produce grains of magnetite as a by-product of their life-cycle processes, enhances MS values on such historic graves [62], whereas others suggest that they are not present in sufficient quantities in soil to cause such an effect and that it may be due to Iron supply linked to climate [44].

Clearly there are important variables to consider for MS as a search technique, for example, the background depositional environment, with urban environments proving problematic, but soil type does not appear to be an important variable although it is in other forensic geophysical techniques, e.g. for GPR, bulk ground conductivity and electrical resistivity surveys. In addition, magnetic surveys in urban environments may suffer from above-ground cultural noise whereas MS surveys may not due to the sensor being placed directly on the ground. Table 2 provides a MS update on suggested forensic geophysics techniques for various target searches for the readers information.

4. Conclusions and further work

Magnetic susceptibility surveys show great potential in forensic search from the case studies shown in this paper. MS equipment is relatively cheap to acquire compared to other geophysical methods, robust and portable in the field, with simple data collection and little processing required to pinpoint anomalous areas, as long as significant background measurements have been taken. It also shows great versatility to successfully detect various buried forensic objects, disturbed ground and surface burnt areas in a variety of soil types and depositional environments.

The next stage is to use this technique in actual forensic searches to determine its usefulness where the target location is unknown. It would also be of great value to measure MS values over disturbed ground where the disturbance date was known, if varied disturbance age surveys were obtained progressively back through time, then potentially crucial cross plots of disturbance age versus geophysical response could be created. Figure 9 shows an example of this from the year-long test hole study detailed in Section 2.2. This would be very useful for search teams to ascertain disturbance age of suspect features before any intrusive investigations are undertaken which may indeed rule out the need for intrusive investigations if results suggest no recent disturbance had taken place. One such depositional environment where such data could be obtained would be marked graves in graveyards and cemeteries with known burial/headstone records. It would also be useful to repeat a modern burial with added Iron/organic matter to determine if this is measurable with existing MS technologies.

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FIGURE CAPTIONS

FIG. 1. Magnetic susceptibility equipment test. a. The ten sample positions (marked) on relatively homogeneous Granite blocks, with the 30 cm diameter surface probe also shown. b. Bar graph of average Bartington™ MS2D survey results (10 measurements at 1s duration) at each test position, with three separate surveys over 1 day (see key).

FIG. 2. Magnetic susceptibility over disturbed ground test. **a**. Photograph of the test profile on Keele University campus with 30cm diameter Bartington™ MS2D surface probe and laptop acquisition also shown. **b**. Line graph of average repeated (see key for dates) survey results (6 measurements at 1s duration) at each test position. **c**. Line graph of graph shown in b with control values subtracted. Error bars have been moved for clarity.

FIG. 3. Photographs of; a. cotton T-shirt and; b. trousers burnt during the study. Site photographs of **c**. burnt surface remains and; d. burnt remains overturned into underlying soil. e. Graph of Bartington™ MS1 survey results on overlain 2D profiles with target locations marked (arrow).

FIG. 4. Magnetic susceptibility over buried forensic targets. **a.** Site photograph and; **b.** after domestic patio laid respectively. MS processed, gridded and contoured map-view data plots of; **c**. pre-burial control, **d**. post-burial grass and; **e**. post-burial domestic patio environments respectively. Buried forensic target (see key) positions marked in c-e. Modified from [2].

FIG. 5. Magnetic susceptibility over simulated urban clandestine grave. a. Site photograph showing simulated grave location and grave contents (inset) of clothed plastic resin human skeleton. Modified from [39]. b. Mapview close-up of the simulated grave (dotted rectangle) of magnetic susceptibility (dots) acquired 1 month after burial.

FIG. 6. Coastal clandestine grave study in Southport, U.K. **a**. Photograph of simulated grave in Marram grass sand dunes and 2D profile position marked **b**. 2D MS profile collected in sand dunes (see a for position). **c**. Photograph of simulated grave on foreshore. **d**. 2D MS profile collected on foreshore (see c for position). Modified from [37].

FIG. 7. Unmarked 19th Century grave in a church graveyard, U.K. **a**. Photograph of suspected grave location shown by slight surface topographic depression. **b**. Plan-view digital contoured surface of Bartington™ MS1 MS survey results with suspected position marked.

FIG. 8. Historic Anglo-Saxon grave study in East Anglia, U.K. **a**. Digital gridded surface generated from Bartington™ MS2D meter. Modified from [62]. **b**. Subsequent photograph of excavated remains.

FIG. 9. Test hole graph cross-plot of average mid-hole (0.5 m) magnetic susceptibility measurements against post-burial interval (days) with linear regression co-efficient also shown (see text).

TABLE CAPTIONS

TABLE 1. Summary of key statistics of research studies detailed in this paper and where further information is available.

Table 2. Generalised table to indicate potential of search techniques(s) success for buried target(s) assuming optimum equipment configurations. Note this table does not differentiate between target size, burial depth/age and other important specific factors (see text). Key: ● Good; ◍ Medium; ○ Poor chances of success. The dominant sand | clay soil end-types are detailed where appropriate for simplicity, therefore not including peat, cobbles etc. types (more wide ranging summary of geophysical techniques versus soil types can be found in [33]). Modified from [1].

ABSTRACT

There are various techniques available for forensic search teams to employ to successfully detect a buried object. Near-surface geophysical search methods have been dominated by ground penetrating radar but recently other techniques, such as electrical resistivity, have become more common. This paper discusses magnetic susceptibility as a simple surface search tool illustrated by various research studies. These suggest magnetic susceptibility to be a relatively low cost, quick and effective tool to determine disturbed ground above buried objects and burnt surface remains. Further research should collect datasets over objects of known burial ages for comparison purposes and used in forensic search cases to validate the technique.

Keywords; forensic science; forensic geophysics; search; magnetic susceptibility

1. Introduction

For a successful criminal conviction to occur, it is often essential to locate forensically important evidence [1]. The forensic objects being searched for vary from illegally buried weapons [2-3] and explosives [4], landmines and improvised explosive devices or IEDs [5], drugs and weapons caches [6] to clandestine graves of murder victims [7] and mass genocide graves [8]. In such situations, burials are usually shallow, less than 3 m below ground level or bgl [9-10]. In addition, the disposal of toxic waste in illegal dumps is a significant and growing issue [11-12]. Water-based forensic geoscience surveys have also been undertaken to assist police and environmental divers, especially in water with poor visibility or large search areas, see [13-16].

Forensic search methods vary widely, for example, in the UK a search strategist is usually involved in a case at an early stage to decide upon the highest probability of search success [17], whereas in other countries a search may not be methodical, investigations may not be standardised and a variety of techniques are undertaken, depending upon local experience [18]. [19] also detail how illegal disposal of waste has to be detected and characterized, before a criminal charge can be brought, with US environmental crime investigation approaches detailed in [20]. Metal detector search teams [21] and specially trained search dogs [22-23] are both commonly used during either initial investigations or as part of a phased sequential programme.

Geoscientific methods are being increasingly utilised and reported upon by forensic search teams for the detection and location of clandestinely buried material [1]. These generally start from the large-scale remote sensing methods [24-26], aerial and ultraviolet photography [9,27], thermal imaging [28], to ground-based observations of vegetation changes [29], surface geomorphology changes [30], soil type [17] and depositional environment(s) [27], near-surface geophysics [1], diggability surveys [17] and probing of anomalous areas [31-32] before topsoil removal [29] and finally controlled excavation and recovery [9].

Near-surface geophysical methods rely on there being a detectable physical contrast between the target and the background (or host) materials (see [33]). Although geophysical methods for forensic search is dominated by ground penetrating radar or GPR [1], a multi-method phased approach is suggested as best practise and is reviewed in [1]. For example, both Electro-Magnetics or EM [34] and its reciprocal electrical resistivity [35] techniques are relatively fast to acquire and resulting anomalous areas can then be further investigated by higher resolution methods. GPR has also been shown to not be optimal in certain search environments, for example in wooded environments [34], water-logged [36], saline-rich [37], clay-rich [38] and heterogeneous [39] soil types, these soil types significantly attenuating radar signal amplitudes. Metal detectors are actually active EM methods relying on metallic objects being good conductors and transmitting their own secondary EM field in response to the instruments' primary EM field (see [3,6]), whereas magnetic methods are passive measurements which measure variations in the Earth's magnetic field due to nearby objects [33,40]. Magnetic surveys have proved not to be optimal in forensic (e.g. [8,41]) and control search studies [42], as they commonly suffer interference from both above- and below-ground non-target objects [33].

All substance have magnetic properties and, when a magnetic field is applied to soil and rock, the degree of magnetization can be measured as the magnetic susceptibility or MS in SI dimensionless units [43]. MS causes are complex and are a combination of dia-, para- and ferro/ferri-magnetism (see [33] for more information). There are wide variations in measured MS reported between different rock and soil types (e.g. [44]) with the largest values being partly attributable to the relative proportions of magnetic minerals present in the material. In soils, the presence of the ferrimagnetic mineral maghemite (Fe_2O_3, γ-Fe_2O_3) has a dominant effect on the magnetic susceptibility and is a low-temperature, oxidisation weathering product of the strongly magnetic minerals magnetite and titanomagnetite [45]. MS has therefore been used for site soil characterisation (e.g. [46]), forensic trace evidence (e.g. see [47-49]) and environmental forensic pollution studies [50-54].

Magnetic susceptibility surface surveys have also been used for quality control checking of magnetic surveys (see [39]), but they have not been used as a forensic search technique to-date, presumably due to their stated 6 cm penetration below ground level or bgl [55-56]. MS has been shown to have poorly resolved a simulated clandestine grave in an urban depositional environment [39]. They are, however, commonly used in archaeological searches (e.g. see [46,57-58]), and have been shown to successfully locate areas of historic surface burning as the weakly magnetic iron oxide minerals in the soil (e.g. hematite and goethite) are transformed into the highly magnetic minerals magnetite and maghemite through heating/burning (e.g. [59-61]). This paper aims to validate the potential usefulness of magnetic susceptibility surface surveys as a forensic search technique through the use of seven illustrative forensic research studies with varying targets and post-burial ages, soil types and depositional environments. Three of these have been previously published but will allow a more wide ranging view of the technique in different forensic search scenarios. It will also be briefly compared to other, more commonly utilised forensic geophysics techniques and finally suggest best practise for such MS surveys.

2. Case studies

2.1 Magnetic Susceptibility equipment surface survey test

In order to confirm the magnetic susceptibility (MS) technique for sample measurement repeatability and reliability, a simple test was devised using a Bartington™ MS2D meter with 0.3 m diameter surface probe. Two relatively homogeneous rock Granite blocks had 4 and 6 sample positions, respectively, repeatedly measured for their magnetic susceptibility (Fig. 1a). Each sample position was measured ten times for its MS at 1 s duration, with the instrument being zeroed between each sample position. The MS survey process was also repeated at 09:00, 13:00 and 17:00 over one day. The local air temperature varied between 16 °C – 18 °C over the survey period.

The MS meter sample position repeatability was very good between surveys (Fig. 1b), with an average and maximum sample position repeat measurement difference of 11.3×10^{-6} and 19.9×10^{-6} respectively. The MS measured data reliability at each sample position was also very good, with SD average survey values of 7×10^{-6}, 1×10^{-6} and 2×10^{-6} for the three respective surveys. The minor sample measurement variations between repeat surveys were thought to primarily be due to slightly different sample positions although this was deliberately kept to a minimum. This test therefore gave confidence in MS equipment operation and sample measurement repeatability and reliability.

2.2 Hole surface survey monitoring test

A field monitoring surface study was undertaken to quantify if the MS technique could be used both to detect disturbed ground and to determine if measured values changed over a one-year study period when compared to background measurements. This should prove if this method detects disturbed ground when no forensic object is present and if this is measureable over one year post-disturbance. A 1 m long survey line was therefore permanently marked by plastic pegs on a quiet semi-rural depositional environment of Keele University campus (Fig. 2a). A 0.2 m by 0.2 m sized hole ~0.1 m deep into the sand loam soil was created ~0.4 m - ~0.6 m along the survey profile, with the excavated grassed earth sod rotated 180° and carefully replaced in the hole. A Bartington™ MS2D meter with a 0.3 m diameter surface probe repeatedly collected magnetic susceptibility measurements every 0.1 m along the 2D profile. Each sample position was measured six times for its MS at 1 s duration, with the instrument being zeroed every five sample positions. The 2D profile was also MS surveyed using the same parameters before the disturbance to act as control. This control line average MS measurement was 637 x 10^{-6} SI with a 35 x 10^{-6} SD, typical MS values for those of a sandy loam brown earth soil that was present here (see Dearing et al. 1996). Average monthly site temperatures were 8 °C and the monthly rainfall average was 77 mm over the survey period.

MS results throughout the survey period showed anomalously high measurements over the area of disturbed ground compared to background values (Fig. 2b). The MS anomaly size was wider than the 0.2 m wide disturbance area; this was to be expected as the 0.3m diameter surface probe would measure part of the disturbance on sampling positions adjacent to the 0.4

m – 0.6 m wide disturbance area. Although there was variation of measurements between surveys, the relative positive anomaly was consistently present, both in its position along the profile and in amplitude (averaging +92 x 10^{-6} SI) when compared to background values. Average MS readings also declined by the later surveys compared to early surveys (*cf.* Fig. 2b). This study gives some confidence that the technique works to consistently detect an area of disturbance in heterogeneous soil over a one year time period in a typically varied temperate climate.

2.3 Burnt clothes surface survey test

A field study was undertaken to quantify if the MS technique could be used to detect a site of burnt clothes left on the ground surface, the same target under overturned soil and finally once they have been removed. A 5 m long survey line was therefore again marked in a quiet semi-rural depositional environment of Keele University campus. Two cotton T-shirts (Fig. 3a) and jogging trousers (Fig. 3b) were carefully burnt using 0.5 L of domestic kerosene within brick-contained 0.5 m x 0.5 m areas (Fig. 3c) along the profile, before one was overturned into the underlying soil (Fig. 3d). The bricks were present to stop any potential ash contamination from spreading during burning but were subsequently removed. The profile was MS surveyed by a Bartington™ MS1 meter with a 0.3 m diameter surface probe every 0.25 m along the 2D profile, before the surface clothes were scraped clear by a metallic spade before being re-surveyed.

MS results showed significant variability between surveys; the highest anomaly (~2.5 times that of relative background values) was surprisingly that of the burnt clothes underneath the overturned soil; the next highest anomaly (~2 times) was the burnt clothes left on the surface and the final MS survey with the ash scraped clear was difficult to differentiate from that of background values (Fig. 3e).

2.4 Buried weapons case study

A field study was undertaken to determine if the MS technique could detect simulated forensic buried objects in a semi-rural environment on Keele University campus, U.K. This had the same soil type as the two previously described case studies. Simulated forensic objects included a replica Colt 0.45 calibre handgun, domestic stainless steel kitchen breadknives, a UK metallic mortar ammunition box and decommissioned WW1 and WW2 allied hand grenades (see Fig. 4a and [2] for information). Objects were buried ~0.15 m below the ground surface in a non-ordered configuration before the excavated material was then used to re-fill each hand-dug hole back to ground level. Multi-geophysical methods were utilised to establish optimum search detection techniques over both grass and domestic patio environments, as well as creating a suite of datasets for search teams to utilise and compare their datasets to in such forensic search areas. A Bartington™ MS1 meter with a 0.3 m diameter surface probe collected magnetic susceptibility measurements every 0.25 m along 0.25 m spaced 2D profiles over a 5 m by 5 m surface area before burial, after burial (Fig. 4a) and again after the domestic patio was laid (Fig. 4b). MS measurements were then despiked to remove isolated anomalous values, de-trending to remove long-wavelength site trends and a minimum curvature algorithm used to create a digital gridded surface. The site was also surveyed by other near-surface instruments for comparison [2].

MS surveys were successful in detecting the buried objects in both the grass and domestic burial scenarios (cf. Fig. 4d-e), only the control objects (1-2) were not resolved in the grass survey although note the handgun (9) was poorly resolved during both post-burial surveys. It was also interesting to note the relative MS contrasts of target against background values were much higher (~5 times) for the grass scenario compared to (~twice) for the domestic patio scenario but both were detectable.

2.5 Urban simulated clandestine grave case study

A field study was undertaken to determine if the MS technique could detect a simulated clandestine burial in an urban environment on Staffordshire University campus, U.K. This had a dominantly 'made-ground' clay-rich soil type. The simulated clandestine grave was hand-dug to 0.6 m bgl before a clothed plastic resin skeleton with animal soft tissue and 4.5 L of salt solution added before reburial with the excavated material back to ground level (see Fig. 5a and [39] for information). Multi-geophysical methods were then used to establish optimum search techniques, one of these being a Bartington™ MS1 meter with a 0.3 m diameter surface probe, collecting magnetic susceptibility measurements every 0.5 m along 0.5 m spaced 2D profiles over a 6 m by 5 m surface area. MS measurements were then despiked to remove isolated anomalous values and a minimum curvature algorithm used to create a digital gridded surface.

The MS survey was not that successful at resolving the simulated clandestine grave (Fig. 5b), whilst relatively high values (~1.5 times) were measured over the target, compared to background values, there were also at least 4 other positions having similar MS measured values. This study therefore gave less confidence that this technique would be useful in such urban depositional environments.

2.6 Coastal simulated clandestine grave case study

A field study was undertaken in a coastal depositional environment in north-west England, U.K. Simulated clandestine graves of murder victims, using an adult-sized, metal-jointed fiberglass mannequin, were created in both sand dunes and on more organic-rich foreshore depositional environments (Fig. 6a/c). Both graves were hand-dug to a depth of 0.5 m and the excavated material was then used to re-fill the grave after the mannequin had been emplaced. Multi-geophysical methods were utilised to establish optimum search detection techniques as well as creating a suite of datasets for search teams to utilise and compare their datasets to in such forensic search areas (see [37] for information). A Bartington™ MS1 meter with a 0.3 m diameter surface probe collected magnetic susceptibility measurements every 0.25 m along respective 5 m long 2D profiles.

MS results from both sites show anomalously high MS measurements recorded over the clandestine graves relative to their background readings (*cf*. Fig. 6b/d) that were both low compared to typical homogeneous dry sand (~30-1000 SI x 10^{-6}) and organic-rich sediments respectively [40]. This is probably due to its salt-rich depositional environment reducing the

MS values. The anomalous readings over both graves were three times that of background readings. It was interesting to note that there was a significant MS measured anomaly over the sand dune simulated clandestine grave (see Fig. 6a), as both the grave contents and the surrounding materials were homogenous quartz sand grains. The wider MS anomaly measured over the foreshore simulated clandestine grave was thought to be dominantly caused by the organic-rich sediments from the grave left on the surface (see Fig. 6c).

2.7 19th Century unmarked grave case study

A geophysical survey was undertaken at St. John of Jerusalem Church in Hackney, London, UK, in order to locate the position of numerous unmarked burials in a graveyard that was closed in 1868. The soil type was a black seat earth. A trial MS survey was undertaken over a suspected grave position that was visually observed to have a rectangular topographic depression (Fig. 7a). A Bartington™ MS1 meter with a 0.3 m diameter surface probe collected magnetic susceptibility measurements every 0.25 m along 0.5 m survey lines within a 4 m by 4 m survey area. MS measurements were then despiked to remove isolated anomalous values, and a minimum curvature algorithm used to create a digital gridded surface.

MS results show anomalously high MS measurements recorded (~three times) over the suspected unmarked grave, compared to background values (Fig. 7b). The approximate anomaly size (~ 1.75 m x 1 m) is also what would be expected for an adult-sized burial in such a graveyard. Within the anomaly area itself two sampling positions are very high compared to all the other MS measurements at the site. It is now known if there was indeed a burial present here due to a lack of archaeological excavation.

2.8 Anglo-Saxon unmarked grave study case study

A near-surface geophysical survey was undertaken at RAF Lakenheath in East Anglia, UK, to determine the location of possible inhumations within an Anglo-Saxon grave following the removal of topsoil (see [62]). A Bartington™ MS2D meter with a 0.1 m diameter surface probe collected MS measurements every 0.1 m along 0.1 m survey lines across a 1.4 m by 2 m survey area identified from soil coloration. MS measurements were then despiked to remove isolated anomalous values, and a minimum curvature algorithm used to create a digital gridded surface (Fig. 8a).

Subsequent archaeological excavation found the isolated adult skeletal remains were in surprisingly good condition given the known acidic nature of the surrounding soils (Fig.8b); the archaeological recording of the recovered remains have been superimposed onto the MS dataset for comparison (Fig. 8a). Clearly there is a relatively good visual comparison recorded between relatively the relative high MS values (~5 times), compared to background values, with the subsequent excavated remains.

3. Discussion

The initial rock granite MS survey test clearly showed excellent repeatability and reliability of measured surface MS survey results in a relatively homogenous medium. The instrument used gives similar results to other MS meters shown by other authors (see [56]). There was also little measureable diurnal variation observed in recorded measurements, in contrast to other magnetic surface surveys, e.g. the proton precession and alkali vapour magnetometers, which do require diurnal correction during data processing to be undertaken (e.g. see [40,42]). The MS equipment also seemed to have little variation in re-acquired sample position measurements that was similarly observed to both electrical resistivity and GPR shielded antennae in other studies (e.g. [2]), most probably due to similar operational procedure of having direct contact with the ground; this both negates any potential variability of instrument height as experienced with typically utilised magnetic instruments and reduces potential above-ground sources of interference.

The field monitoring surface study of disturbed ground was informative; not only did it show a relatively consistent MS peak compared to background values even though no forensic object was emplaced, but that it was also still detectable up to a year after disturbance. This is important forensically, evidence of disturbed ground could be crucial to gain forensic trace evidence, as has been observed in Balkan Civil War primary and secondary clandestine grave depositions [63] and for landmine clearance operations [64]. Whilst areas of disturbed ground have been shown to be electrically detectable from background relative values due to a combination of increased soil porosity and hence water content [65] this does widely vary depending upon seasonality, moisture content, soil type and moisture content [66]; therefore the MS method looks to be more consistent and detectable over this time period which is promising.

The burnt clothes study was informative as it showed MS could be used to detect the position of such forensic targets which could be very important for criminal trace evidential purposes (see [67-68]). Other research has additionally shown that when organic matter in a soil burns at ~600-700 ^{0}C it can change the soil's weakly magnetic minerals to magnetite and maghemite on re-oxidation as the burn ceases, all of which further increase relative MS values ([46,69-70]). Mathematical calculations can also be undertaken from MS data to estimate the approximate historic fire temperature ([71]).

The buried weapons study was useful as these are commonly required by forensic search teams to locate for evidential purposes. Whilst metal detector and GPR are the commonly used geophysical techniques for such searches [1], the MS survey had the best detection success rates of all the techniques trialled [2]; this is important as excavating a domestic patio is obvious time consuming and costly (see [4]). MS surveys also give a numerical value for sample positions which is less usual in metal detectors. The domestic patio scenario also reduced the relative contrast of MS values above the forensic targets from five times to twice that of the background values but they were still detectable. It is also interesting to note that the MS survey was successful even though the target burial depth was deeper than the instruments' perceived penetration depth of 6cm; therefore suggesting the instrument was picking up the soil disturbance over the target rather than the target itself.

The urban simulated clandestine grave study was useful as, despite the MS survey not being that successful at delineating the search target, it provides valuable information on using the technique in common urban search scenarios (see [4]). It may be that MS is not an optimal search technique in such urban depositional environments due to the amount of disturbed ground that will be present and thus providing difficulty in differentiating from the target versus the background MS values.

The coastal simulated clandestine grave study was again found to successfully detect the target burial although this was ~0.5 m bgl (Fig. 5); it is suggested that the disturbance was again being detected. Whilst this would be expected on the foreshore scenario as there were a variety of organic-rich and quartz sand heterogeneous soil present, in the dune scenario the soil was comprised of relatively homogenous quartz sand grains and thus little material change would have been present here. The foreshore example shows one of the potential difficulties with this technique in detecting a buried object if the site has been recently disturbed; it would be very difficult to detect which area had the forensic target of interest present. The MS survey technique compared favourably to both GPR and resistivity in the sand dune scenario with it being much better on the foreshore as both the GPR and resistivity methods were poor in this depositional environment (see [37]).

The 19th Century unmarked grave study showed that forensic targets over 100 years old could be detectable using the MS method although subsequent archaeological excavations have not been undertaken; other authors have used depressions and geophysics to successfully detect unmarked burials (e.g. [72]) but other studies have found that suspect burial positions may not, in fact, be what was suspected [73]. Clearly more geophysical data over marked burials with known burial dates would assist in determining if MS could be a useful technique in this arena and, indeed how long they would be detectable for.

The historic unmarked grave study is very useful as it shows that MS can potentially still be used as a successful detection method even with a post-burial date of 1,000+ years. Unlike most of the other case studies, it is probably not disturbed soil that would be causing a measureable MS difference from background values. It has been suggested that it is both Iron loading from haemoglobin and the presence of magnetotactic bacteria, which produce grains of magnetite as a by-product of their life-cycle processes, enhances MS values on such historic graves [62], whereas others suggest that they are not present in sufficient quantities in soil to cause such an effect and that it may be due to Iron supply linked to climate [44].

Clearly there are important variables to consider for MS as a search technique, for example, the background depositional environment, with urban environments proving problematic, but soil type does not appear to be an important variable although it is in other forensic geophysical techniques, e.g. for GPR, bulk ground conductivity and electrical resistivity surveys. In addition, magnetic surveys in urban environments may suffer from above-ground cultural noise whereas MS surveys may not due to the sensor being placed directly on the ground. Table 2 provides a MS update on suggested forensic geophysics techniques for various target searches for the readers information.

4. Conclusions and further work

Magnetic susceptibility surveys show great potential in forensic search from the case studies shown in this paper. MS equipment is relatively cheap to acquire, robust and portable in the field, with simple data collection and little processing required to pinpoint anomalous areas, as long as significant background measurements have been taken. It also shows great versatility to successfully detect various buried forensic objects, disturbed ground and surface burnt areas in a variety of soil types and depositional environments.

The next stage is to use this technique in actual forensic searches to determine its usefulness where the target location is unknown. It would also be of great value to measure MS values over disturbed ground where the disturbance date was known, if varied disturbance age surveys were obtained progressively back through time, then potentially crucial cross plots of disturbance age versus geophysical response could be created. Figure 9 shows an example of this from the year-long test hole study detailed in Section 2.2. This would be very useful for search teams to ascertain disturbance age of suspect features before any intrusive investigations are undertaken which may indeed rule out the need for intrusive investigations if results suggest no recent disturbance had taken place. One such depositional environment where such data could be obtained would be marked graves in graveyards and cemeteries with known burial/headstone records. It would also be useful to repeat a modern burial with added Iron/organic matter to determine if this is measurable with existing MS technologies.

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FIGURE CAPTIONS

FIG. 1. Magnetic susceptibility equipment test. a. The ten sample positions (marked) on relatively homogeneous Granite blocks, with the 30 cm diameter surface probe also shown. b. Bar graph of average Bartington™ MS2D survey results (10 measurements at 1s duration) at each test position, with three separate surveys over 1 day (see key).

FIG. 2. Magnetic susceptibility over disturbed ground test. **a**. Photograph of the test profile on Keele University campus with 30cm diameter Bartington™ MS2D surface probe and laptop acquisition also shown. **b**. Line graph of average repeated (see key for dates) survey results (6 measurements at 1s duration) at each test position. **c**. Line graph of graph shown in b with control values subtracted. Error bars have been moved for clarity.

FIG. 3. Photographs of; a. cotton T-shirt and; b. trousers burnt during the study. Site photographs of **c**. burnt surface remains and; d. burnt remains overturned into underlying soil. e. Graph of Bartington™ MS1 survey results on overlain 2D profiles with target locations marked (arrow).

FIG. 4. Magnetic susceptibility over buried forensic targets. **a.** Site photograph and; **b.** after domestic patio laid respectively. MS processed, gridded and contoured map-view data plots of; **c**. pre-burial control, **d**. post-burial grass and; **e**. post-burial domestic patio environments respectively. Buried forensic target (see key) positions marked in c-e. Modified from [2].

FIG. 5. Magnetic susceptibility over simulated urban clandestine grave. a. Site photograph showing simulated grave location and grave contents (inset) of clothed plastic resin human skeleton. Modified from [39]. b. Mapview close-up of the simulated grave (dotted rectangle) of magnetic susceptibility (dots) acquired 1 month after burial.

FIG. 6. Coastal clandestine grave study in Southport, U.K. **a**. Photograph of simulated grave in Marram grass sand dunes and 2D profile position marked **b**. 2D MS profile collected in sand dunes (see a for position). **c**. Photograph of simulated grave on foreshore. **d**. 2D MS profile collected on foreshore (see c for position). Modified from [37].

FIG. 7. Unmarked 19th Century grave in a church graveyard, U.K. **a**. Photograph of suspected grave location shown by slight surface topographic depression. **b**. Plan-view digital contoured surface of Bartington™ MS1 MS survey results with suspected position marked.

FIG. 8. Historic Anglo-Saxon grave study in East Anglia, U.K. **a**. Digital gridded surface generated from Bartington™ MS2D meter. Modified from [62]. **b**. Subsequent photograph of excavated remains.

FIG. 9. Test hole graph cross-plot of average mid-hole (0.5 m) magnetic susceptibility measurements against post-burial interval (days) with linear regression co-efficient also shown (see text).

TABLE CAPTIONS

TABLE 1. Summary of key statistics of research studies detailed in this paper and where further information is available.

Table 2. Generalised table to indicate potential of search techniques(s) success for buried target(s) assuming optimum equipment configurations. Note this table does not differentiate between target size, burial depth/age and other important specific factors (see text). Key: ● Good; ◍ Medium; ○ Poor chances of success. The dominant sand | clay soil end-types are detailed where appropriate for simplicity, therefore not including peat, cobbles etc. types (more wide ranging summary of geophysical techniques versus soil types can be found in [33]). Modified from [1].

Figure1

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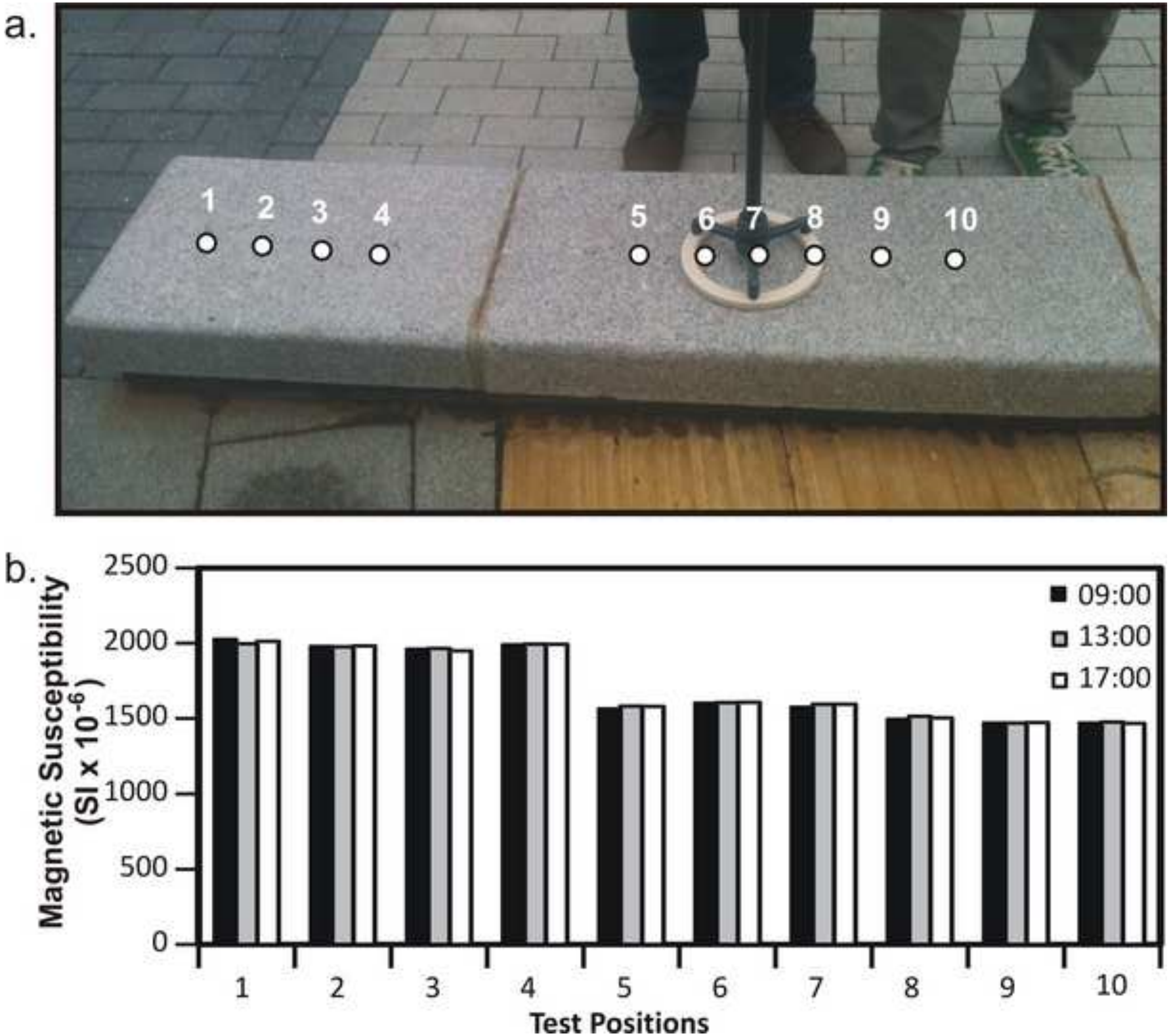

Figure3

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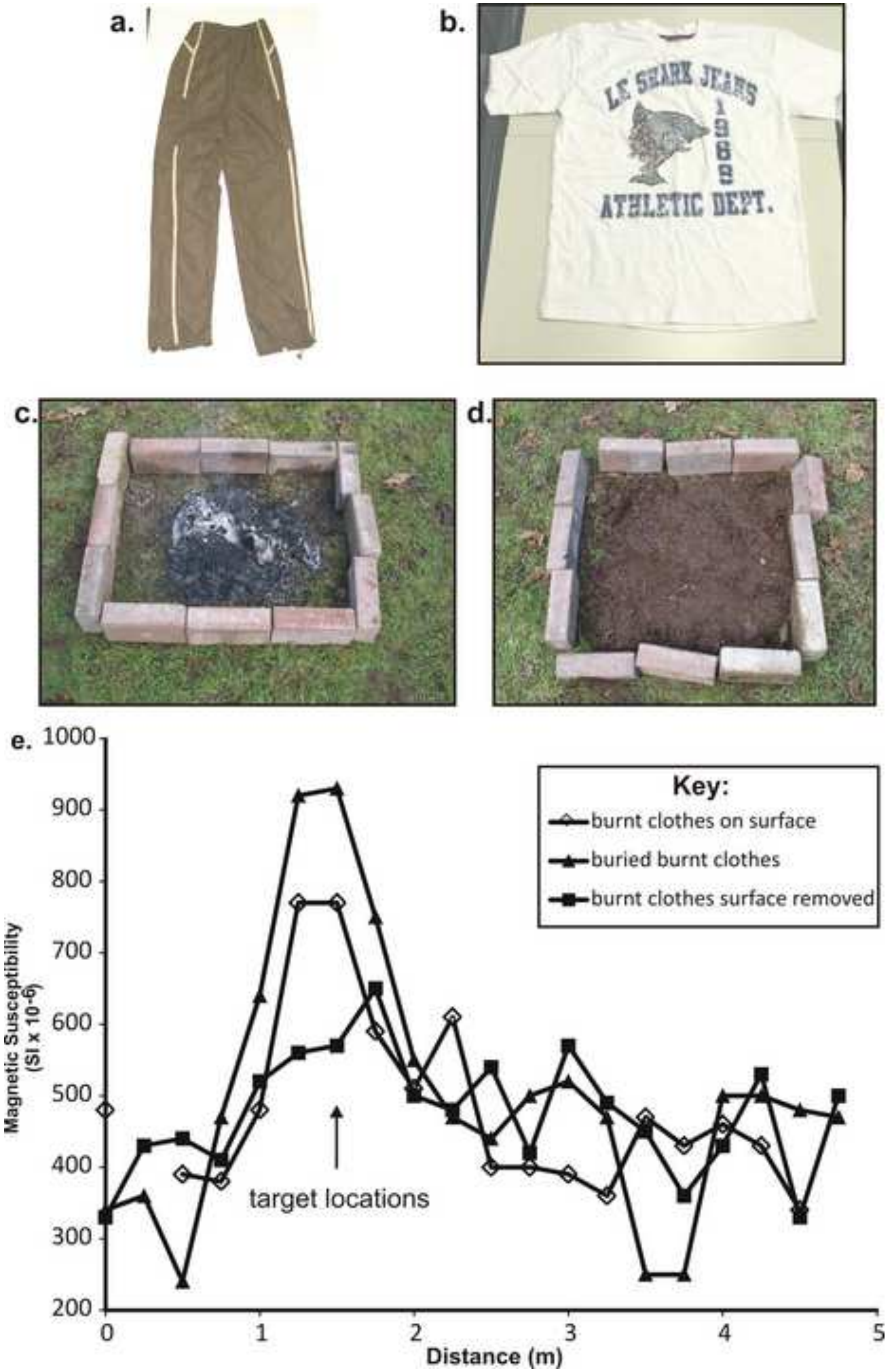

Figure4

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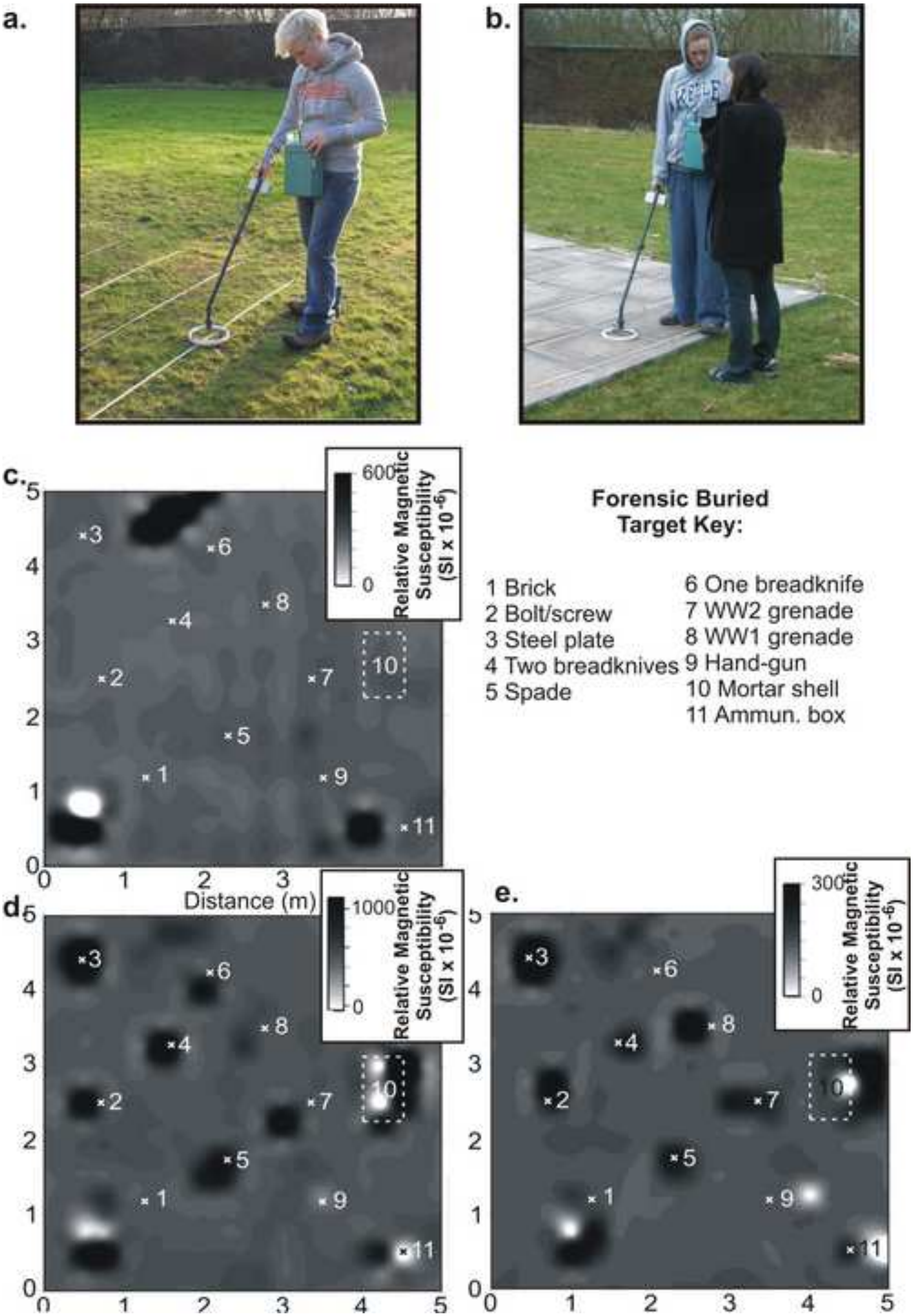

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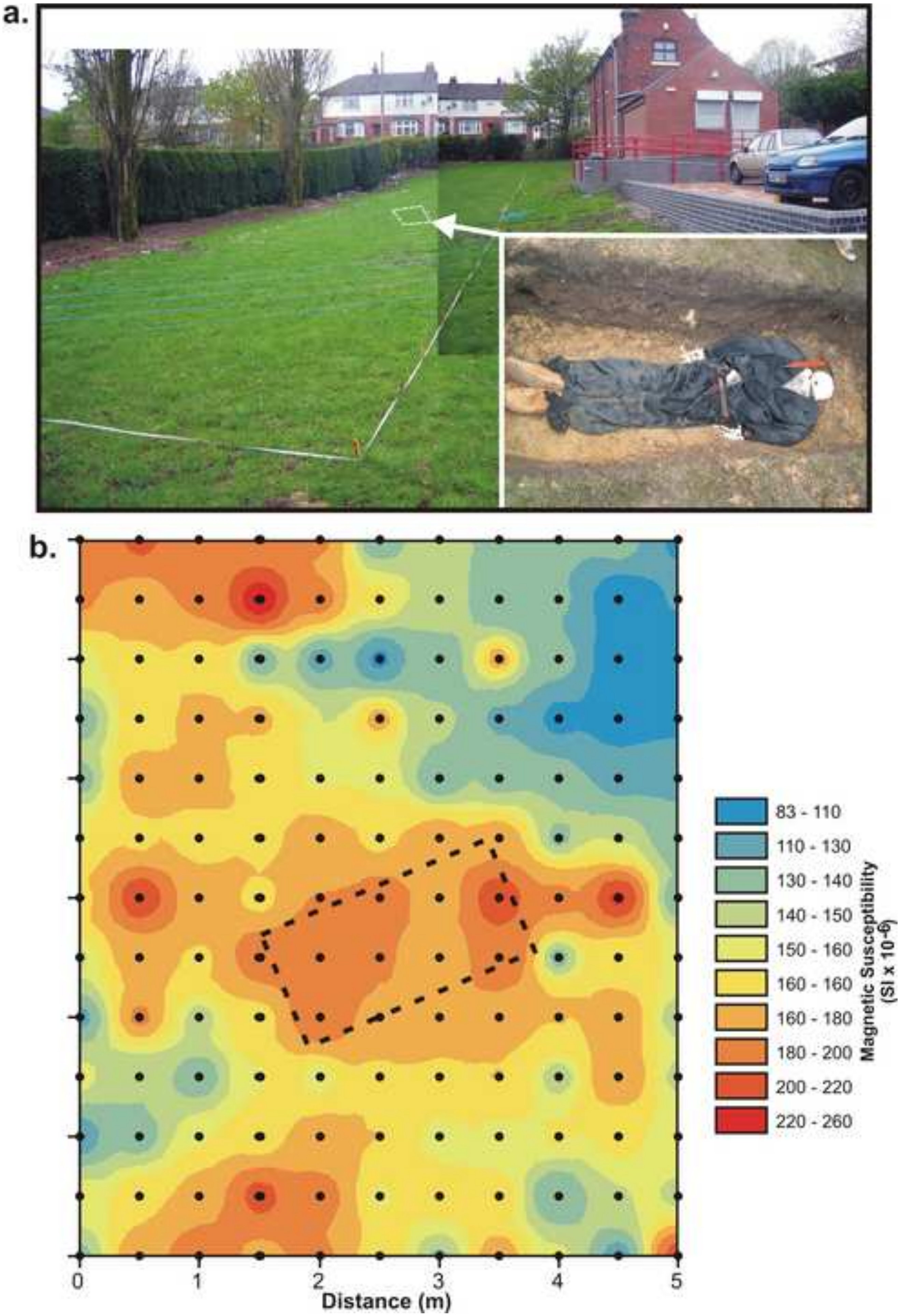

Figure6

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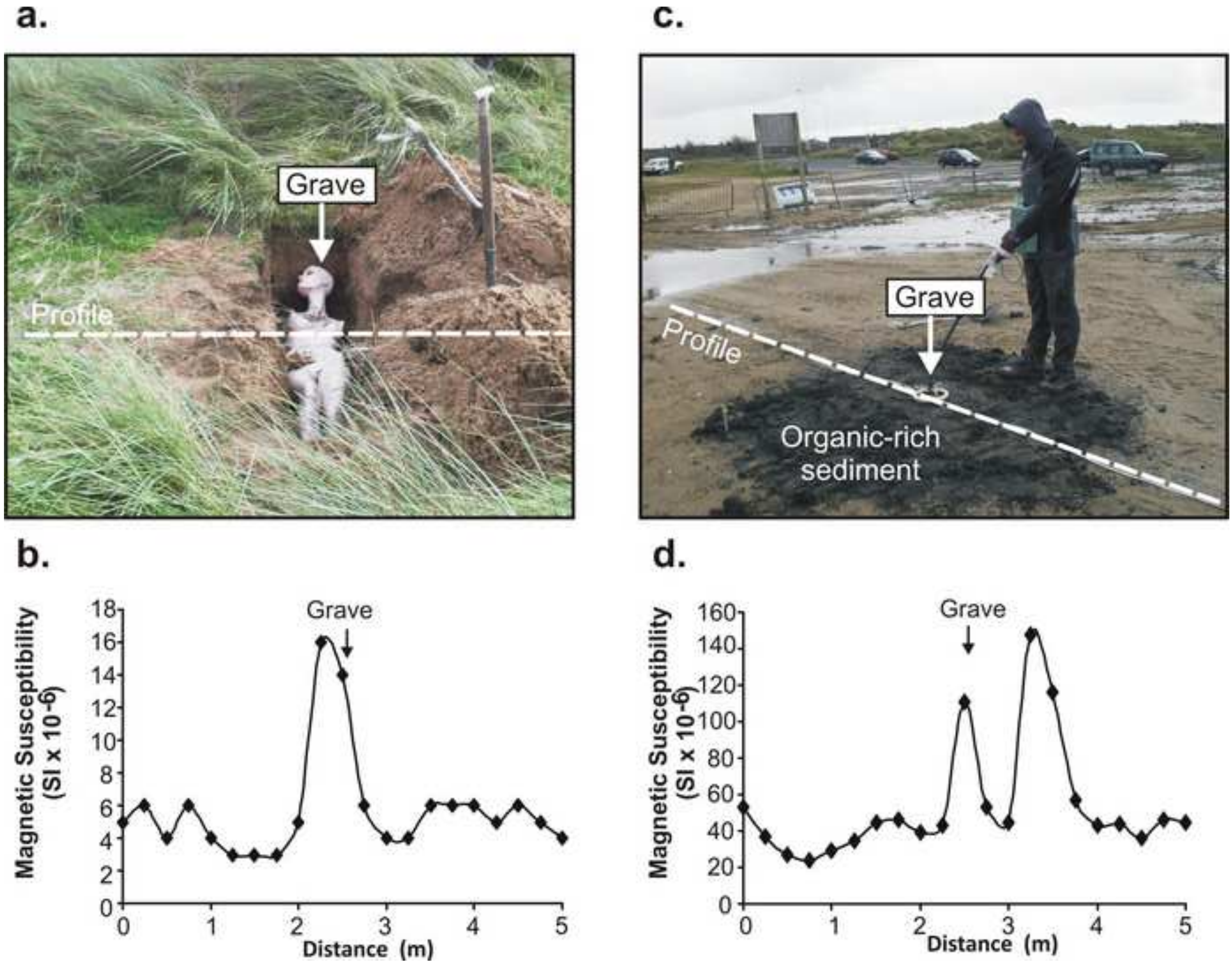

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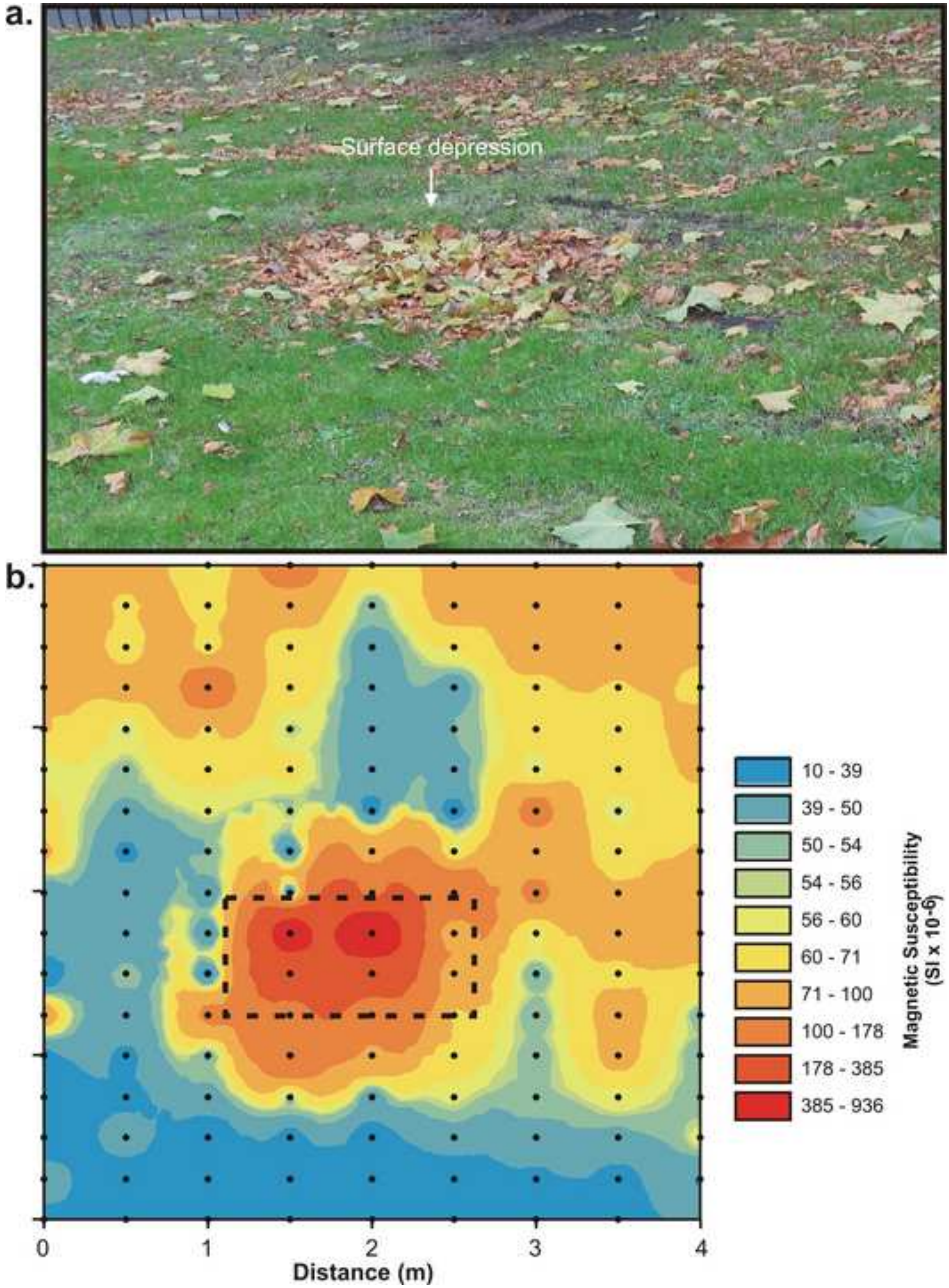

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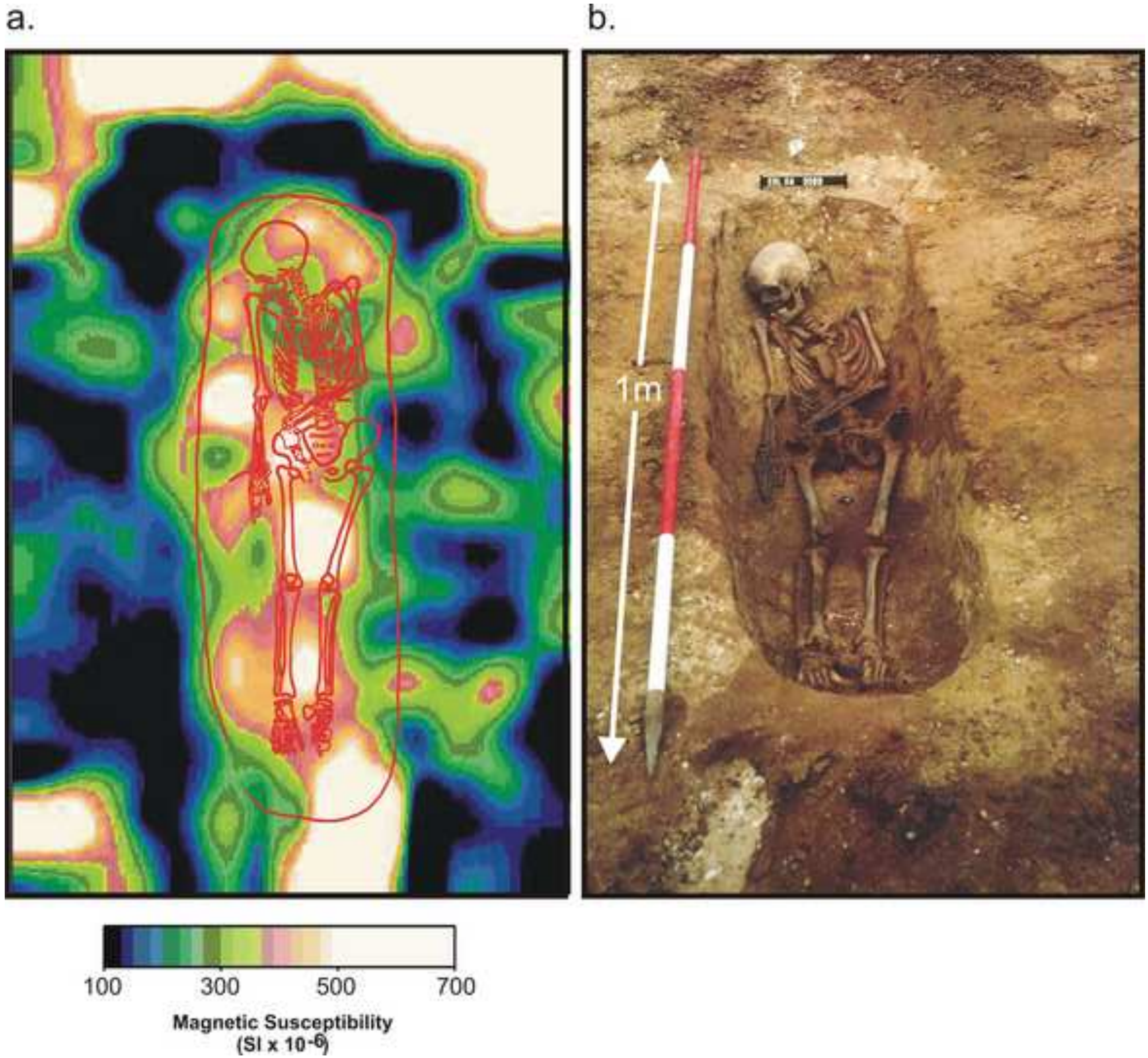

Figure2

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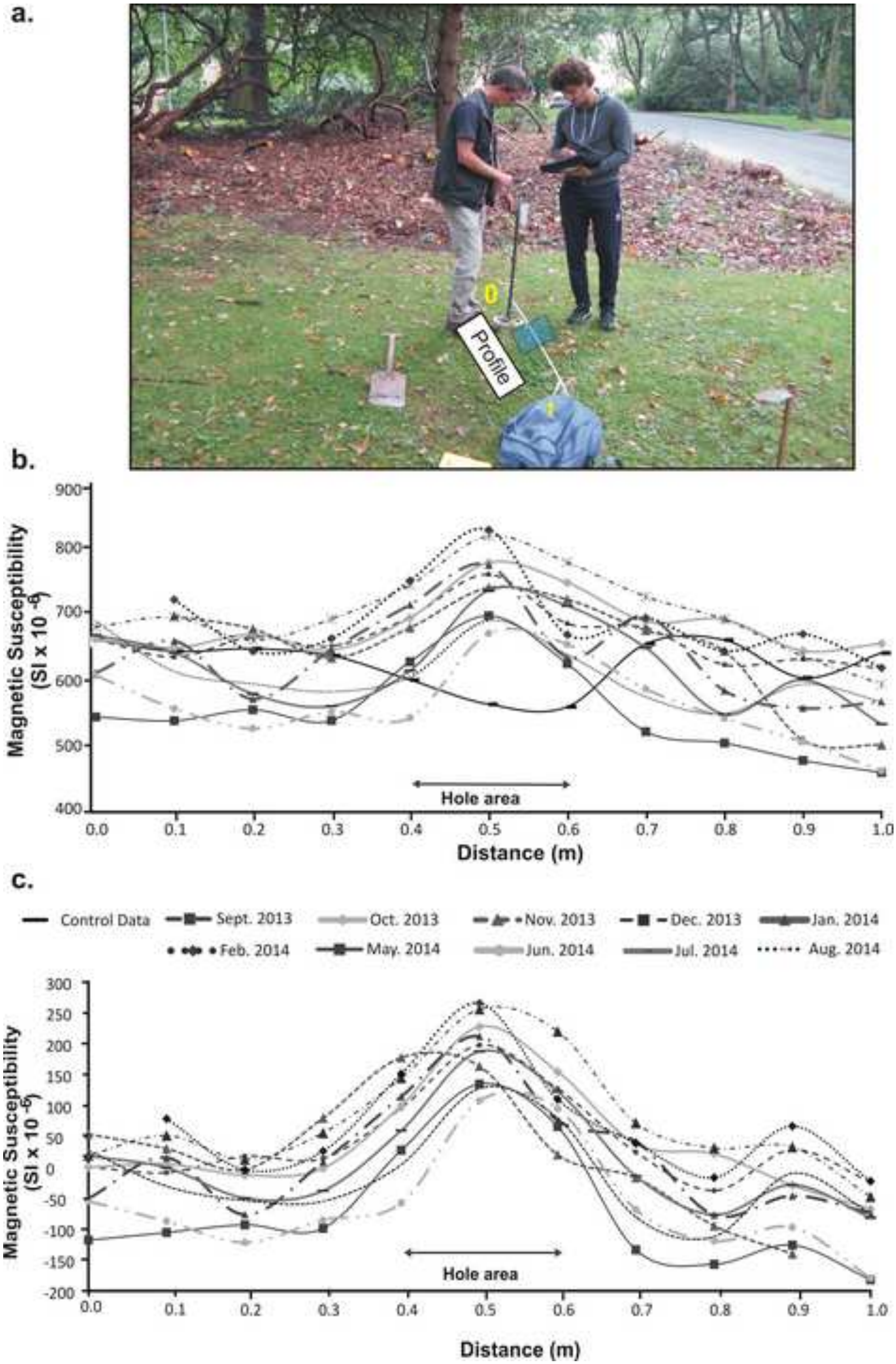

Figure9

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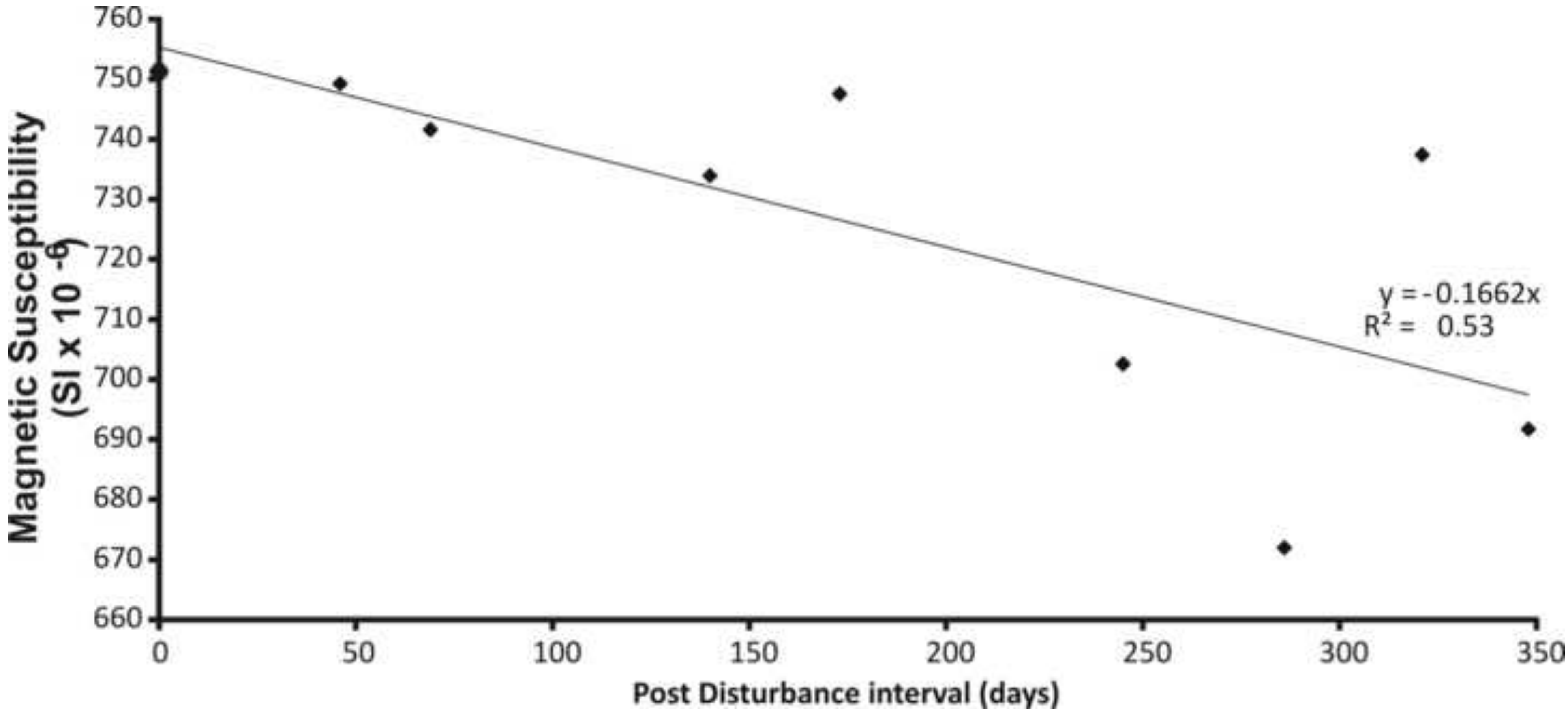

Table1

Target(s)	Post-burial date	Soil type	Depositional environment	Sample spacing (m)	Further Info.
Monitoring disturbed ground (2.2)	0 – 1 year	Sandy loam	Semi-rural	0.1	N/A
Burnt clothes on surface & buried (2.3)	2 months	Sandy loam	Semi-rural	0.25 x 0.25	N/A
Buried weapons (2.4)	0	Sandy loam	Semi-rural	0.25 x 0.25	[2]
Clandestine grave (2.5)	1 month	Made-ground clay rich	Urban	0.5 x 0.5	[39])
Clandestine grave (2.6)	0	Salt-rich sand	Coastal	0.25	[37]
Historic grave (2.7)	150+ years	Black earth	Semi-urban	0.25 x 0.5	N/A
Anglo-Saxon grave (2.8)	1,000+ years	Acidic	Rural	0.1 x 0.1	[61]

TABLE 1. Summary of key statistics of research studies detailed in this paper and where further information is available.

Table2

Target(s)	**Near-Surface Geophysics**						
Soil type: sand | clay	Seis-mology /	Cond-uctivity	Resist-ivity	GPR	Mag-netics	Metal detector	Magnetic suscept-ibility
Unmarked grave(s)	Poor | Poor	Medium | Medium	Good | Good	Good | Medium	Medium | Medium	Poor | Poor	Good | Good
Clandestine grave(s)	Poor | Poor	Medium | Medium	Good | Good	Good | Medium	Good | Good	Medium | Medium	Good | Good
UXOs/ IEDs	Poor | Poor	Medium | Medium	Good | Good	Good | Medium	Good | Good	Good | Good	Good | Good
Weapons	Poor | Poor	Medium | Medium	Medium | Medium	Medium | Medium	Good | Good	Good | Good	Good | Good
Drug / cash dumps	Poor | Poor	Medium | Medium	Medium | Medium	Medium | Medium	Medium | Medium	Medium | Medium	Good | Good
Illegal waste	Medium | Good	Good | Good	Good | Good	Good | Medium	Medium | Medium	Good | Good	Medium | Medium
Common depositional environment							
Woods	Poor	Medium	Poor	Poor	Good	Good	Good
Rural	Good	Good	Good	Good	Good	Good	Good
Urban	Medium	Poor	Poor	Medium	Poor	Medium	Poor
Coastal	Good	Poor	Medium	Poor	Good	Good	Good

Table 2. Generalised table to indicate potential of search techniques(s) success for buried target(s) assuming optimum equipment configurations. Note this table does not differentiate between target size, burial depth/age and other important specific factors (see text). Key: ● Good; ◍ Medium; ○ Poor chances of success. The dominant sand | clay soil end-types are detailed where appropriate for simplicity, therefore not including peat, cobbles etc. types (more wide ranging summary of geophysical techniques versus soil types can be found in [33]). Modified from [1].

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Response to reviewers:

The very minor changes requested by the 2 reviewers have been undertaken. These were:

1) In reply to R2, graphical abstract changed from grave image to grave magnetic susceptibility image.

2) In reply to R1, 'relative to other geophysical methods' has been added to abstract/conclusions and equipment cost (and weight) added in methods section.

3) In reply to R2, the stated 6cm depth of penetration of the technique in soil is explicitly mentioned in introduction (L77) with 2 references listed for further information and also in the discussion (L318).

4) In reply to R2, ‘in a variety of soil types’ have been added to the abstract as it is explicitly already mentioned that magnetic susceptibility is not affected by soil types, it is how much magnetic material is in the soil.

We have taken the liberty of also attaching the manuscript with ‘track changes’ on to show the very minor changes from the original submitted manuscript.