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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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## The use of magnetic susceptibility as a forensic search tool

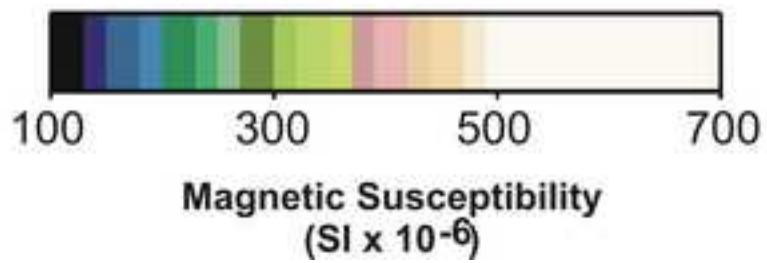
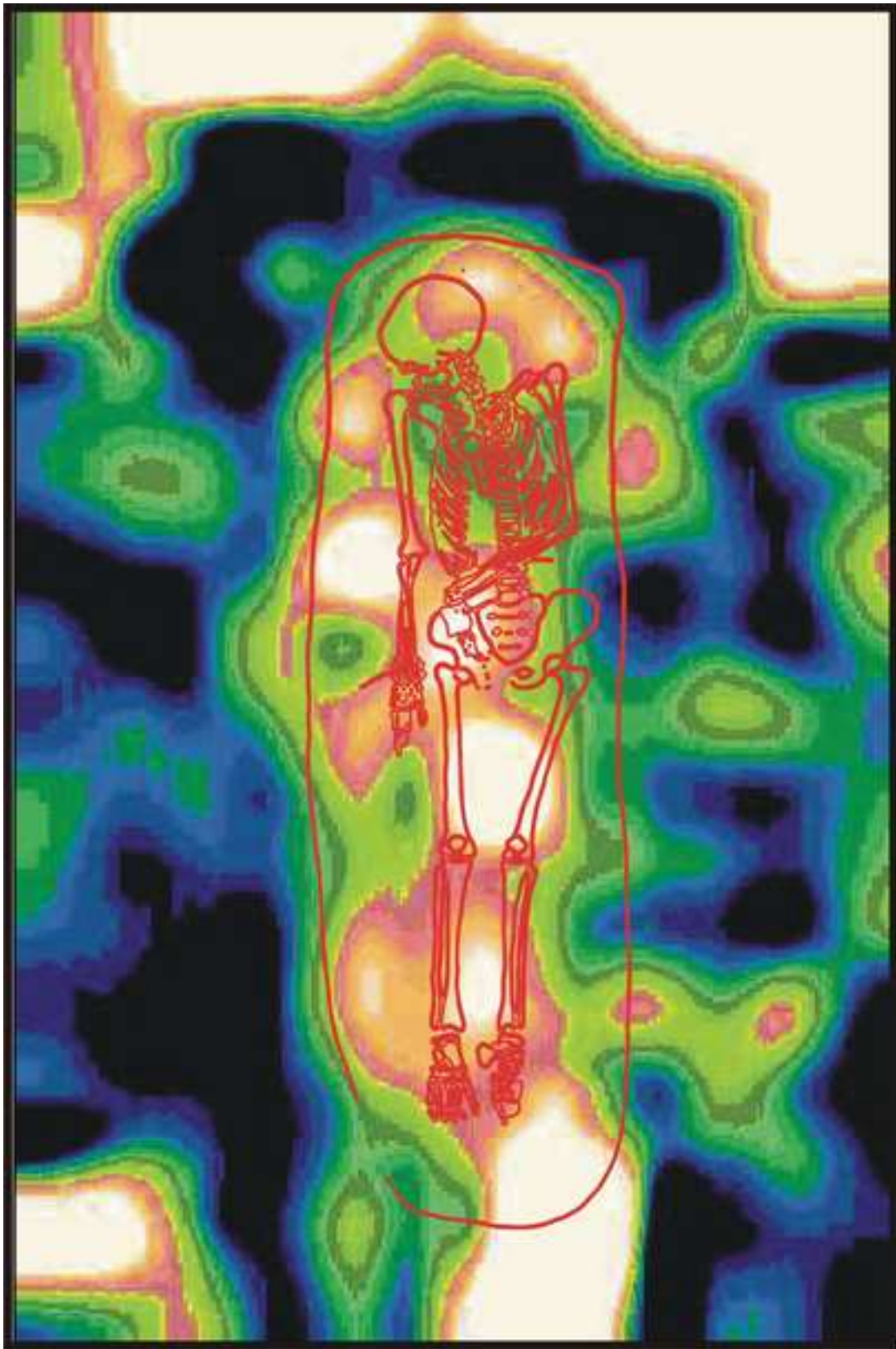
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Highlights:

- 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

1 **ABSTRACT**

2

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

12

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

14

15

16 **1. Introduction**

17

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

27

28 Forensic search methods vary widely, for example, in the UK a search strategist is usually  
29 involved in a case at an early stage to decide upon the highest probability of search success  
30 [17], whereas in other countries a search may not be methodical, investigations may not be  
31 standardised and a variety of techniques are undertaken, depending upon local experience  
32 [18]. [19] also detail how illegal disposal of waste has to be detected and characterized,  
33 before a criminal charge can be brought, with US environmental crime investigation  
34 approaches detailed in [20]. Metal detector search teams [21] and specially trained search  
35 dogs [22-23] are both commonly used during either initial investigations or as part of a  
36 phased sequential programme.

37

38 Geoscientific methods are being increasingly utilised and reported upon by forensic search  
39 teams for the detection and location of clandestinely buried material [1]. These generally  
40 start from the large-scale remote sensing methods [24-26], aerial and ultraviolet photography  
41 [9,27], thermal imaging [28], to ground-based observations of vegetation changes [29],  
42 surface geomorphology changes [30], soil type [17] and depositional environment(s) [27],  
43 near-surface geophysics [1], diggability surveys [17] and probing of anomalous areas [31-32]  
44 before topsoil removal [29] and finally controlled excavation and recovery [9].

45

46 Near-surface geophysical methods rely on there being a detectable physical contrast between  
47 the target and the background (or host) materials (see [33]). Although geophysical methods  
48 for forensic search are dominated by ground penetrating radar or GPR [1], a multi-method  
49 phased approach is suggested as best practise and is reviewed in [1]. For example, both  
50 Electro-Magnetics or EM [34] and its reciprocal electrical resistivity [35] techniques are  
51 relatively fast to acquire and resulting anomalous areas can then be further investigated by  
52 higher resolution methods. GPR has also been shown to not be optimal in certain search  
53 environments, for example in wooded environments [34], water-logged [36], saline-rich [37],  
54 clay-rich [38] and heterogeneous [39] soil types, these soil types significantly attenuating  
55 radar signal amplitudes. Metal detectors are actually active EM methods relying on metallic  
56 objects being good conductors and transmitting their own secondary EM field in response to  
57 the instruments' primary EM field (see [3,6]), whereas magnetic methods are passive  
58 measurements which measure variations in the Earth's magnetic field due to nearby objects  
59 [33,40]. Magnetic surveys have proved not to be optimal in forensic (e.g. [8,41]) and control  
60 search studies [42], as they commonly suffer interference from both above- and below-  
61 ground non-target objects [33].



62

63 All substance have magnetic properties and, when a magnetic field is applied to soil and rock,  
64 the degree of magnetization can be measured as the magnetic susceptibility or MS in SI  
65 dimensionless units [43]. MS causes are complex and are a combination of dia-, para- and  
66 ferro/ferri-magnetism (see [33] for more information). There are wide variations in  
67 measured MS reported between different rock and soil types (e.g. [44]) with the largest  
68 values being partly attributable to the relative proportions of magnetic minerals present in the  
69 material. In soils, the presence of the ferrimagnetic mineral maghemite ( $\text{Fe}_2\text{O}_3$ ,  $\gamma\text{-Fe}_2\text{O}_3$ ) has  
70 a dominant effect on the magnetic susceptibility and is a low-temperature, oxidation  
71 weathering product of the strongly magnetic minerals magnetite and titanomagnetite [45].  
72 MS has therefore been used for site soil characterisation (e.g. [46]), forensic trace evidence  
73 (e.g. see [47-49]) and environmental forensic pollution studies [50-54].

74

75 Magnetic susceptibility surface surveys have also been used for quality control checking of  
76 magnetic surveys (see [39]), but they have not been used as a forensic search technique to-  
77 date, presumably due to their stated 6 cm penetration below ground level or bgl, although this  
78 is a function of effective response of the proportion of magnetic materials present [55-56].  
79 MS has been shown to have poorly resolved a simulated clandestine grave in an urban  
80 depositional environment [39]. They are, however, commonly used in archaeological  
81 searches (e.g. see [46,57-58]), and have been shown to successfully locate areas of historic  
82 surface burning as the weakly magnetic iron oxide minerals in the soil (e.g. hematite and  
83 goethite) are transformed into the highly magnetic minerals magnetite and maghemite  
84 through heating/burning (e.g. [59-61]). This paper aims to validate the potential usefulness of  
85 magnetic susceptibility surface surveys as a forensic search technique through the use of

86 seven illustrative forensic research studies with varying targets and post-burial ages, soil  
87 types and depositional environments. Three of these have been previously published but will  
88 allow a more wide ranging view of the technique in different forensic search scenarios. It  
89 will also be briefly compared to other, more commonly utilised forensic geophysics  
90 techniques and finally suggest best practise for such MS surveys.

91

92 **2. Case studies**

93

94 *2.1 Magnetic Susceptibility equipment surface survey test*

95

96 In order to confirm the magnetic susceptibility (MS) technique for sample measurement  
97 repeatability and reliability, a simple test was devised using a Bartington™ MS2D meter with  
98 0.3 m diameter surface probe that costs ~£3,000, weighs 1.9 Kg and was connected to a  
99 ruggedised PC laptop with Bartsoft™ v.4 data acquisition software. Two relatively  
100 homogeneous rock Granite blocks had 4 and 6 sample positions, respectively, repeatedly  
101 measured for their magnetic susceptibility (Fig. 1a). Each sample position was measured ten  
102 times for its MS at 1 s duration, with the instrument being zeroed between each sample  
103 position. The MS survey process was also repeated at 09:00, 13:00 and 17:00 over one day.  
104 The local air temperature varied between 16 °C – 18 °C over the survey period.

105

106 The MS meter sample position repeatability was very good between surveys (Fig. 1b), with  
107 an average and maximum sample position repeat measurement difference of  $11.3 \times 10^{-6}$  and  
108  $19.9 \times 10^{-6}$  respectively. The MS measured data reliability at each sample position was also  
109 very good, with SD average survey values of  $7 \times 10^{-6}$ ,  $1 \times 10^{-6}$  and  $2 \times 10^{-6}$  for the three  
110 respective surveys. The minor sample measurement variations between repeat surveys were  
111 thought to primarily be due to slightly different sample positions although this was  
112 deliberately kept to a minimum. This test therefore gave confidence in MS equipment  
113 operation and sample measurement repeatability and reliability.

114

115 2.2 Hole surface survey monitoring test

116

117 A field monitoring surface study was undertaken to quantify if the MS technique could be  
118 used both to detect disturbed ground and to determine if measured values changed over a  
119 one-year study period when compared to background measurements. This should prove if  
120 this method detects disturbed ground when no forensic object is present and if this is  
121 measureable over one year post-disturbance. A 1 m long survey line was therefore  
122 permanently marked by plastic pegs on a quiet semi-rural depositional environment of Keele  
123 University campus (Fig. 2a). A 0.2 m by 0.2 m sized hole ~0.1 m deep into the sand loam  
124 soil was created ~0.4 m - ~0.6 m along the survey profile, with the excavated grassed earth  
125 sod rotated 180° and carefully replaced in the hole. A Bartington™ MS2D meter with a 0.3  
126 m diameter surface probe repeatedly collected magnetic susceptibility measurements every  
127 0.1 m along the 2D profile. Each sample position was measured six times for its MS at 1 s  
128 duration, with the instrument being zeroed every five sample positions. The 2D profile was  
129 also MS surveyed using the same parameters before the disturbance to act as control. This  
130 control line average MS measurement was  $637 \times 10^{-6}$  SI with a  $35 \times 10^{-6}$  SD, typical MS  
131 values for those of a sandy loam brown earth soil that was present here (see Dearing et al.  
132 1996). Average monthly site temperatures were 8 °C and the monthly rainfall average was  
133 77 mm over the survey period.

134

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

139 m – 0.6 m wide disturbance area. Although there was variation of measurements between  
140 surveys, the relative positive anomaly was consistently present, both in its position along the  
141 profile and in amplitude (averaging  $+92 \times 10^{-6}$  SI) when compared to background values.  
142 Average MS readings also declined by the later surveys compared to early surveys (*cf.* Fig.  
143 2b). This study gives some confidence that the technique works to consistently detect an area  
144 of disturbance in heterogeneous soil over a one year time period in a typically varied  
145 temperate climate.

146

### 147 *2.3 Burnt clothes surface survey test*

148

149 A field study was undertaken to quantify if the MS technique could be used to detect a site of  
150 burnt clothes left on the ground surface, the same target under overturned soil and finally  
151 once they have been removed. A 5 m long survey line was therefore again marked in a quiet  
152 semi-rural depositional environment of Keele University campus. Two cotton T-shirts (Fig.  
153 3a) and jogging trousers (Fig. 3b) were carefully burnt using 0.5 L of domestic kerosene  
154 within brick-contained 0.5 m x 0.5 m areas (Fig. 3c) along the profile, before one was  
155 overturned into the underlying soil (Fig. 3d). The bricks were present to stop any potential  
156 ash contamination from spreading during burning but were subsequently removed. The  
157 profile was MS surveyed by a Bartington™ MS1 meter with a 0.3 m diameter surface probe  
158 every 0.25 m along the 2D profile, before the surface clothes were scraped clear by a metallic  
159 spade before being re-surveyed.

160

161 MS results showed significant variability between surveys; the highest anomaly (~2.5 times  
162 that of relative background values) was surprisingly that of the burnt clothes underneath the

163 overturned soil; the next highest anomaly (~2 times) was the burnt clothes left on the surface  
164 and the final MS survey with the ash scraped clear was difficult to differentiate from that of  
165 background values (Fig. 3e).

166

#### 167 *2.4 Buried weapons case study*

168

169 A field study was undertaken to determine if the MS technique could detect simulated  
170 forensic buried objects in a semi-rural environment on Keele University campus, U.K. This  
171 had the same soil type as the two previously described case studies. Simulated forensic  
172 objects included a replica Colt 0.45 calibre handgun, domestic stainless steel kitchen  
173 breadknives, a UK metallic mortar ammunition box and decommissioned WW1 and WW2  
174 allied hand grenades (see Fig. 4a and [2] for information). Objects were buried ~0.15 m  
175 below the ground surface in a non-ordered configuration before the excavated material was  
176 then used to re-fill each hand-dug hole back to ground level. Multi-geophysical methods  
177 were utilised to establish optimum search detection techniques over both grass and domestic  
178 patio environments, as well as creating a suite of datasets for search teams to utilise and  
179 compare their datasets to in such forensic search areas. A Bartington™ MS1 meter with a 0.3  
180 m diameter surface probe collected magnetic susceptibility measurements every 0.25 m along  
181 0.25 m spaced 2D profiles over a 5 m by 5 m surface area before burial, after burial (Fig. 4a)  
182 and again after the domestic patio was laid (Fig. 4b). MS measurements were then despiked  
183 to remove isolated anomalous values, de-trending to remove long-wavelength site trends and  
184 a minimum curvature algorithm used to create a digital gridded surface. The site was also  
185 surveyed by other near-surface instruments for comparison [2].

186

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

193

#### 194 *2.5 Urban simulated clandestine grave case study*

195

196 A field study was undertaken to determine if the MS technique could detect a simulated  
197 clandestine burial in an urban environment on Staffordshire University campus, U.K. This  
198 had a dominantly ‘made-ground’ clay-rich soil type. The simulated clandestine grave was  
199 hand-dug to 0.6 m bgl before a clothed plastic resin skeleton with animal soft tissue and 4.5 L  
200 of salt solution added before reburial with the excavated material back to ground level (see  
201 Fig. 5a and [39] for information). Multi-geophysical methods were then used to establish  
202 optimum search techniques, one of these being a Bartington™ MS1 meter with a 0.3 m  
203 diameter surface probe, collecting magnetic susceptibility measurements every 0.5 m along  
204 0.5 m spaced 2D profiles over a 6 m by 5 m surface area. MS measurements were then  
205 despiked to remove isolated anomalous values and a minimum curvature algorithm used to  
206 create a digital gridded surface.

207

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

213

#### 214 *2.6 Coastal simulated clandestine grave case study*

215

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

226

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



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

237

### 238 *2.7 19<sup>th</sup> Century unmarked grave case study*

239

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

249

250 MS results show anomalously high MS measurements recorded (~three times) over the  
251 suspected unmarked grave, compared to background values (Fig. 7b). The approximate  
252 anomaly size (~ 1.75 m x 1 m) is also what would be expected for an adult-sized burial in  
253 such a graveyard. Within the anomaly area itself two sampling positions are very high

254 compared to all the other MS measurements at the site. It is now known if there was indeed a  
255 burial present here due to a lack of archaeological excavation.

256

### 257 *2.8 Anglo-Saxon unmarked grave study case study*

258

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

266

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

273

### 274 3. Discussion

275

276 The initial rock granite MS survey test clearly showed excellent repeatability and reliability  
277 of measured surface MS survey results in a relatively homogenous medium. The instrument  
278 used gives similar results to other MS meters shown by other authors (see [56]). There was  
279 also little measureable diurnal variation observed in recorded measurements, in contrast to  
280 other magnetic surface surveys, e.g. the proton precession and alkali vapour magnetometers,  
281 which do require diurnal correction during data processing to be undertaken (e.g. see  
282 [40,42]). The MS equipment also seemed to have little variation in re-acquired sample  
283 position measurements that was similarly observed to both electrical resistivity and GPR  
284 shielded antennae in other studies (e.g. [2]), most probably due to similar operational  
285 procedure of having direct contact with the ground; this both negates any potential variability  
286 of instrument height as experienced with typically utilised magnetic instruments and reduces  
287 potential above-ground sources of interference.

288

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

298 the MS method looks to be more consistent and detectable over this time period which is  
299 promising.

300

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

308

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

320

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

327

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

339

340 The 19<sup>th</sup> Century unmarked grave study showed that forensic targets over 100 years old could  
341 be detectable using the MS method although subsequent archaeological excavations have not  
342 been undertaken; other authors have used depressions and geophysics to successfully detect  
343 unmarked burials (e.g. [72]) but other studies have found that suspect burial positions may  
344 not, in fact, be what was suspected [73]. Clearly more geophysical data over marked burials

345 with known burial dates would assist in determining if MS could be a useful technique in this  
346 arena and, indeed how long they would be detectable for.

347

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

356

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

365

366

367

368 **4. Conclusions and further work**

369

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

377

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

390

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636

637 **FIGURE CAPTIONS**

638

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

643

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

649

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

654

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

659

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

664

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

669

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

673

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

677

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

681

682

683 **TABLE CAPTIONS**

684

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

687

688 **Table 2.** Generalised table to indicate potential of search techniques(s) success for buried  
689 target(s) assuming optimum equipment configurations. Note this table does not differentiate  
690 between target size, burial depth/age and other important specific factors (see text). Key: ●  
691 Good; ● Medium; ○ Poor chances of success. The dominant sand | clay soil end-types are  
692 detailed where appropriate for simplicity, therefore not including peat, cobbles etc. types  
693 (more wide ranging summary of geophysical techniques versus soil types can be found in  
694 [33]). Modified from [1].

695

1 **ABSTRACT**

2

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

12

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

14

15



16 **1. Introduction**

17

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

27

28 Forensic search methods vary widely, for example, in the UK a search strategist is usually  
29 involved in a case at an early stage to decide upon the highest probability of search success  
30 [17], whereas in other countries a search may not be methodical, investigations may not be  
31 standardised and a variety of techniques are undertaken, depending upon local experience  
32 [18]. [19] also detail how illegal disposal of waste has to be detected and characterized,  
33 before a criminal charge can be brought, with US environmental crime investigation  
34 approaches detailed in [20]. Metal detector search teams [21] and specially trained search  
35 dogs [22-23] are both commonly used during either initial investigations or as part of a  
36 phased sequential programme.

37

38 Geoscientific methods are being increasingly utilised and reported upon by forensic search  
39 teams for the detection and location of clandestinely buried material [1]. These generally  
40 start from the large-scale remote sensing methods [24-26], aerial and ultraviolet photography  
41 [9,27], thermal imaging [28], to ground-based observations of vegetation changes [29],  
42 surface geomorphology changes [30], soil type [17] and depositional environment(s) [27],  
43 near-surface geophysics [1], diggability surveys [17] and probing of anomalous areas [31-32]  
44 before topsoil removal [29] and finally controlled excavation and recovery [9].

45

46 Near-surface geophysical methods rely on there being a detectable physical contrast between  
47 the target and the background (or host) materials (see [33]). Although geophysical methods  
48 for forensic search is dominated by ground penetrating radar or GPR [1], a multi-method  
49 phased approach is suggested as best practise and is reviewed in [1]. For example, both  
50 Electro-Magnetics or EM [34] and its reciprocal electrical resistivity [35] techniques are  
51 relatively fast to acquire and resulting anomalous areas can then be further investigated by  
52 higher resolution methods. GPR has also been shown to not be optimal in certain search  
53 environments, for example in wooded environments [34], water-logged [36], saline-rich [37],  
54 clay-rich [38] and heterogeneous [39] soil types, these soil types significantly attenuating  
55 radar signal amplitudes. Metal detectors are actually active EM methods relying on metallic  
56 objects being good conductors and transmitting their own secondary EM field in response to  
57 the instruments' primary EM field (see [3,6]), whereas magnetic methods are passive  
58 measurements which measure variations in the Earth's magnetic field due to nearby objects  
59 [33,40]. Magnetic surveys have proved not to be optimal in forensic (e.g. [8,41]) and control  
60 search studies [42], as they commonly suffer interference from both above- and below-  
61 ground non-target objects [33].

62

63 All substance have magnetic properties and, when a magnetic field is applied to soil and rock,  
64 the degree of magnetization can be measured as the magnetic susceptibility or MS in SI  
65 dimensionless units [43]. MS causes are complex and are a combination of dia-, para- and  
66 ferro/ferri-magnetism (see [33] for more information). There are wide variations in  
67 measured MS reported between different rock and soil types (e.g. [44]) with the largest  
68 values being partly attributable to the relative proportions of magnetic minerals present in the  
69 material. In soils, the presence of the ferrimagnetic mineral maghemite ( $\text{Fe}_2\text{O}_3$ ,  $\gamma\text{-Fe}_2\text{O}_3$ ) has  
70 a dominant effect on the magnetic susceptibility and is a low-temperature, oxidisation  
71 weathering product of the strongly magnetic minerals magnetite and titanomagnetite [45].  
72 MS has therefore been used for site soil characterisation (e.g. [46]), forensic trace evidence  
73 (e.g. see [47-49]) and environmental forensic pollution studies [50-54].

74

75 Magnetic susceptibility surface surveys have also been used for quality control checking of  
76 magnetic surveys (see [39]), but they have not been used as a forensic search technique to-  
77 date, presumably due to their stated 6 cm penetration below ground level or bgl [55-56]. MS  
78 has been shown to have poorly resolved a simulated clandestine grave in an urban  
79 depositional environment [39]. They are, however, commonly used in archaeological  
80 searches (e.g. see [46,57-58]), and have been shown to successfully locate areas of historic  
81 surface burning as the weakly magnetic iron oxide minerals in the soil (e.g. hematite and  
82 goethite) are transformed into the highly magnetic minerals magnetite and maghemite  
83 through heating/burning (e.g. [59-61]). This paper aims to validate the potential usefulness of  
84 magnetic susceptibility surface surveys as a forensic search technique through the use of  
85 seven illustrative forensic research studies with varying targets and post-burial ages, soil

86 types and depositional environments. Three of these have been previously published but will  
87 allow a more wide ranging view of the technique in different forensic search scenarios. It  
88 will also be briefly compared to other, more commonly utilised forensic geophysics  
89 techniques and finally suggest best practise for such MS surveys.

90

91 **2. Case studies**

92

93 *2.1 Magnetic Susceptibility equipment surface survey test*

94

95 In order to confirm the magnetic susceptibility (MS) technique for sample measurement  
96 repeatability and reliability, a simple test was devised using a Bartington™ MS2D meter with  
97 0.3 m diameter surface probe. Two relatively homogeneous rock Granite blocks had 4 and 6  
98 sample positions, respectively, repeatedly measured for their magnetic susceptibility (Fig.  
99 1a). Each sample position was measured ten times for its MS at 1 s duration, with the  
100 instrument being zeroed between each sample position. The MS survey process was also  
101 repeated at 09:00, 13:00 and 17:00 over one day. The local air temperature varied between  
102 16 °C – 18 °C over the survey period.

103

104 The MS meter sample position repeatability was very good between surveys (Fig. 1b), with  
105 an average and maximum sample position repeat measurement difference of  $11.3 \times 10^{-6}$  and  
106  $19.9 \times 10^{-6}$  respectively. The MS measured data reliability at each sample position was also  
107 very good, with SD average survey values of  $7 \times 10^{-6}$ ,  $1 \times 10^{-6}$  and  $2 \times 10^{-6}$  for the three  
108 respective surveys. The minor sample measurement variations between repeat surveys were  
109 thought to primarily be due to slightly different sample positions although this was  
110 deliberately kept to a minimum. This test therefore gave confidence in MS equipment  
111 operation and sample measurement repeatability and reliability.

112

113

114 2.2 Hole surface survey monitoring test

115

116 A field monitoring surface study was undertaken to quantify if the MS technique could be  
117 used both to detect disturbed ground and to determine if measured values changed over a  
118 one-year study period when compared to background measurements. This should prove if  
119 this method detects disturbed ground when no forensic object is present and if this is  
120 measureable over one year post-disturbance. A 1 m long survey line was therefore  
121 permanently marked by plastic pegs on a quiet semi-rural depositional environment of Keele  
122 University campus (Fig. 2a). A 0.2 m by 0.2 m sized hole ~0.1 m deep into the sand loam  
123 soil was created ~0.4 m - ~0.6 m along the survey profile, with the excavated grassed earth  
124 sod rotated 180° and carefully replaced in the hole. A Bartington™ MS2D meter with a 0.3  
125 m diameter surface probe repeatedly collected magnetic susceptibility measurements every  
126 0.1 m along the 2D profile. Each sample position was measured six times for its MS at 1 s  
127 duration, with the instrument being zeroed every five sample positions. The 2D profile was  
128 also MS surveyed using the same parameters before the disturbance to act as control. This  
129 control line average MS measurement was  $637 \times 10^{-6}$  SI with a  $35 \times 10^{-6}$  SD, typical MS  
130 values for those of a sandy loam brown earth soil that was present here (see Dearing et al.  
131 1996). Average monthly site temperatures were 8 °C and the monthly rainfall average was  
132 77 mm over the survey period.

133

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

138 m – 0.6 m wide disturbance area. Although there was variation of measurements between  
139 surveys, the relative positive anomaly was consistently present, both in its position along the  
140 profile and in amplitude (averaging  $+92 \times 10^{-6}$  SI) when compared to background values.  
141 Average MS readings also declined by the later surveys compared to early surveys (*cf.* Fig.  
142 2b). This study gives some confidence that the technique works to consistently detect an area  
143 of disturbance in heterogeneous soil over a one year time period in a typically varied  
144 temperate climate.

145

### 146 *2.3 Burnt clothes surface survey test*

147

148 A field study was undertaken to quantify if the MS technique could be used to detect a site of  
149 burnt clothes left on the ground surface, the same target under overturned soil and finally  
150 once they have been removed. A 5 m long survey line was therefore again marked in a quiet  
151 semi-rural depositional environment of Keele University campus. Two cotton T-shirts (Fig.  
152 3a) and jogging trousers (Fig. 3b) were carefully burnt using 0.5 L of domestic kerosene  
153 within brick-contained 0.5 m x 0.5 m areas (Fig. 3c) along the profile, before one was  
154 overturned into the underlying soil (Fig. 3d). The bricks were present to stop any potential  
155 ash contamination from spreading during burning but were subsequently removed. The  
156 profile was MS surveyed by a Bartington™ MS1 meter with a 0.3 m diameter surface probe  
157 every 0.25 m along the 2D profile, before the surface clothes were scraped clear by a metallic  
158 spade before being re-surveyed.

159

160 MS results showed significant variability between surveys; the highest anomaly (~2.5 times  
161 that of relative background values) was surprisingly that of the burnt clothes underneath the

162 overturned soil; the next highest anomaly (~2 times) was the burnt clothes left on the surface  
163 and the final MS survey with the ash scraped clear was difficult to differentiate from that of  
164 background values (Fig. 3e).

165

#### 166 *2.4 Buried weapons case study*

167

168 A field study was undertaken to determine if the MS technique could detect simulated  
169 forensic buried objects in a semi-rural environment on Keele University campus, U.K. This  
170 had the same soil type as the two previously described case studies. Simulated forensic  
171 objects included a replica Colt 0.45 calibre handgun, domestic stainless steel kitchen  
172 breadknives, a UK metallic mortar ammunition box and decommissioned WW1 and WW2  
173 allied hand grenades (see Fig. 4a and [2] for information). Objects were buried ~0.15 m  
174 below the ground surface in a non-ordered configuration before the excavated material was  
175 then used to re-fill each hand-dug hole back to ground level. Multi-geophysical methods  
176 were utilised to establish optimum search detection techniques over both grass and domestic  
177 patio environments, as well as creating a suite of datasets for search teams to utilise and  
178 compare their datasets to in such forensic search areas. A Bartington™ MS1 meter with a 0.3  
179 m diameter surface probe collected magnetic susceptibility measurements every 0.25 m along  
180 0.25 m spaced 2D profiles over a 5 m by 5 m surface area before burial, after burial (Fig. 4a)  
181 and again after the domestic patio was laid (Fig. 4b). MS measurements were then despiked  
182 to remove isolated anomalous values, de-trending to remove long-wavelength site trends and  
183 a minimum curvature algorithm used to create a digital gridded surface. The site was also  
184 surveyed by other near-surface instruments for comparison [2].



185

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

192

### 193 *2.5 Urban simulated clandestine grave case study*

194

195 A field study was undertaken to determine if the MS technique could detect a simulated  
196 clandestine burial in an urban environment on Staffordshire University campus, U.K. This  
197 had a dominantly ‘made-ground’ clay-rich soil type. The simulated clandestine grave was  
198 hand-dug to 0.6 m bgl before a clothed plastic resin skeleton with animal soft tissue and 4.5 L  
199 of salt solution added before reburial with the excavated material back to ground level (see  
200 Fig. 5a and [39] for information). Multi-geophysical methods were then used to establish  
201 optimum search techniques, one of these being a Bartington™ MS1 meter with a 0.3 m  
202 diameter surface probe, collecting magnetic susceptibility measurements every 0.5 m along  
203 0.5 m spaced 2D profiles over a 6 m by 5 m surface area. MS measurements were then  
204 despiked to remove isolated anomalous values and a minimum curvature algorithm used to  
205 create a digital gridded surface.

206

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

212

### 213 *2.6 Coastal simulated clandestine grave case study*

214

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

225

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

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

236

### 237 *2.7 19<sup>th</sup> Century unmarked grave case study*

238

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

248

249 MS results show anomalously high MS measurements recorded (~three times) over the  
250 suspected unmarked grave, compared to background values (Fig. 7b). The approximate  
251 anomaly size (~ 1.75 m x 1 m) is also what would be expected for an adult-sized burial in  
252 such a graveyard. Within the anomaly area itself two sampling positions are very high

253 compared to all the other MS measurements at the site. It is now known if there was indeed a  
254 burial present here due to a lack of archaeological excavation.

255

## 256 *2.8 Anglo-Saxon unmarked grave study case study*

257

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

265

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

272

273 **3. Discussion**

274

275 The initial rock granite MS survey test clearly showed excellent repeatability and reliability  
276 of measured surface MS survey results in a relatively homogenous medium. The instrument  
277 used gives similar results to other MS meters shown by other authors (see [56]). There was  
278 also little measureable diurnal variation observed in recorded measurements, in contrast to  
279 other magnetic surface surveys, e.g. the proton precession and alkali vapour magnetometers,  
280 which do require diurnal correction during data processing to be undertaken (e.g. see  
281 [40,42]). The MS equipment also seemed to have little variation in re-acquired sample  
282 position measurements that was similarly observed to both electrical resistivity and GPR  
283 shielded antennae in other studies (e.g. [2]), most probably due to similar operational  
284 procedure of having direct contact with the ground; this both negates any potential variability  
285 of instrument height as experienced with typically utilised magnetic instruments and reduces  
286 potential above-ground sources of interference.

287

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

297 the MS method looks to be more consistent and detectable over this time period which is  
298 promising.

299

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

307

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

319

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

326

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

338

339 The 19<sup>th</sup> Century unmarked grave study showed that forensic targets over 100 years old could  
340 be detectable using the MS method although subsequent archaeological excavations have not  
341 been undertaken; other authors have used depressions and geophysics to successfully detect  
342 unmarked burials (e.g. [72]) but other studies have found that suspect burial positions may  
343 not, in fact, be what was suspected [73]. Clearly more geophysical data over marked burials

344 with known burial dates would assist in determining if MS could be a useful technique in this  
345 arena and, indeed how long they would be detectable for.

346

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

355

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

364

365

366



367 **4. Conclusions and further work**

368

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

375

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

388

389

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635

636 **FIGURE CAPTIONS**

637

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

642

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

648

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

653

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

658

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

663

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

668

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

672

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

676

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

680

681



682 **TABLE CAPTIONS**

683

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

686

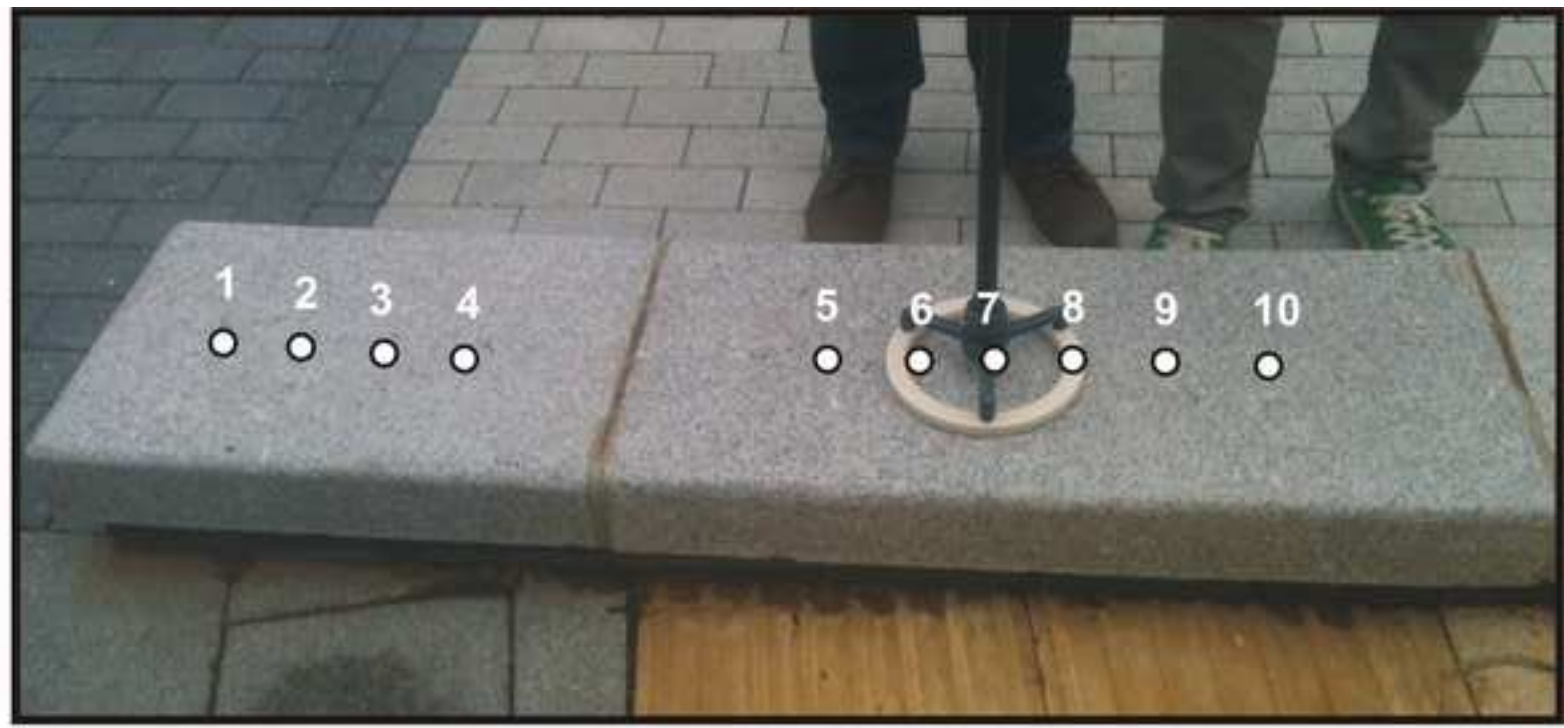
687 **Table 2.** Generalised table to indicate potential of search techniques(s) success for buried  
688 target(s) assuming optimum equipment configurations. Note this table does not differentiate  
689 between target size, burial depth/age and other important specific factors (see text). Key: ●  
690 Good; ● Medium; ○ Poor chances of success. The dominant sand | clay soil end-types are  
691 detailed where appropriate for simplicity, therefore not including peat, cobbles etc. types  
692 (more wide ranging summary of geophysical techniques versus soil types can be found in  
693 [33]). Modified from [1].

694

Figure1

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a.



b.

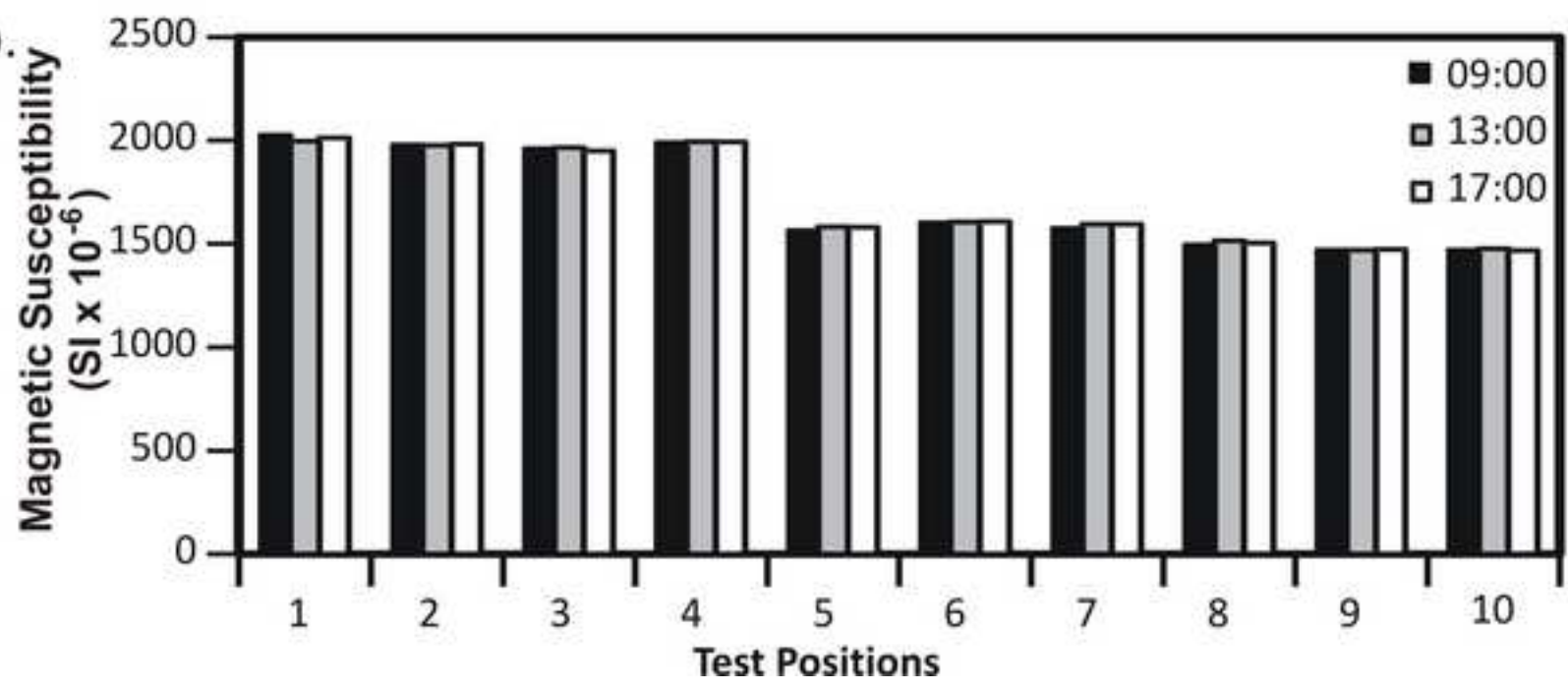


Figure3  
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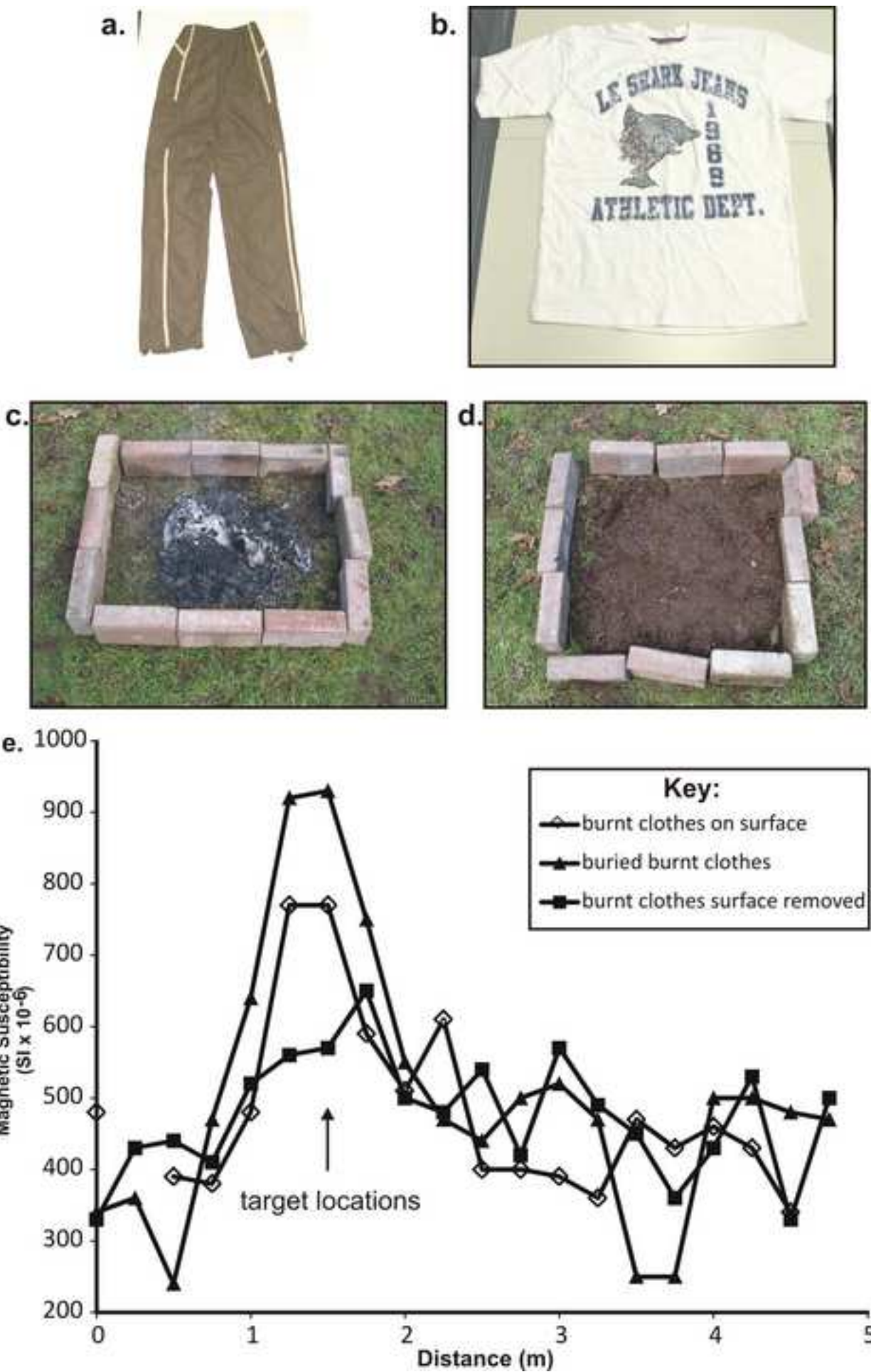
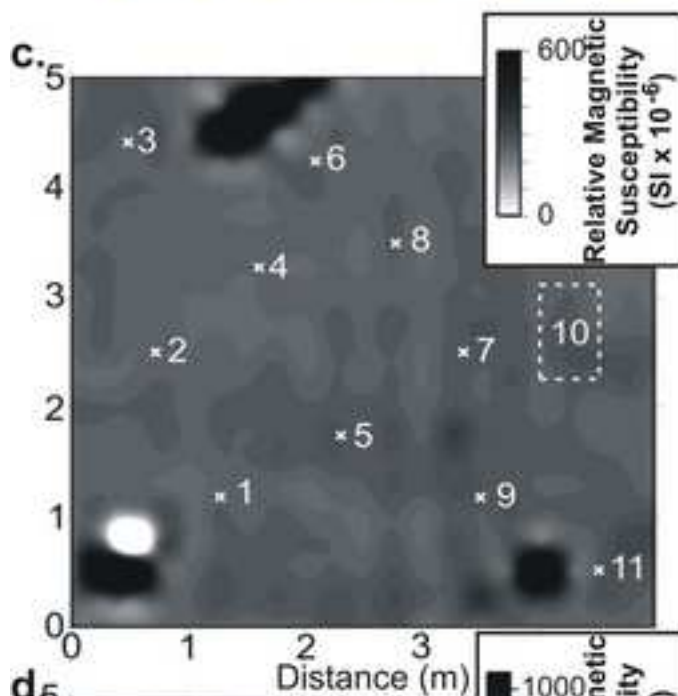


Figure4

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**Forensic Buried Target Key:**

- |                   |                  |
|-------------------|------------------|
| 1 Brick           | 6 One breadknife |
| 2 Bolt/screw      | 7 WW2 grenade    |
| 3 Steel plate     | 8 WW1 grenade    |
| 4 Two breadknives | 9 Hand-gun       |
| 5 Spade           | 10 Mortar shell  |
|                   | 11 Ammun. box    |

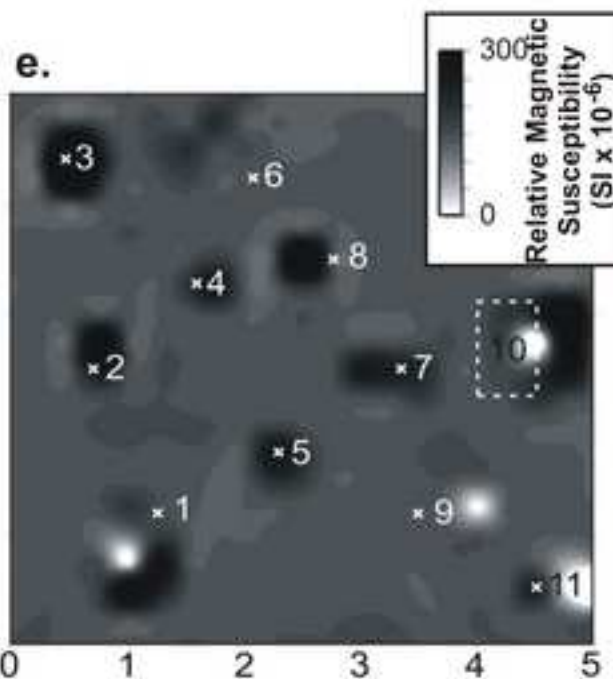
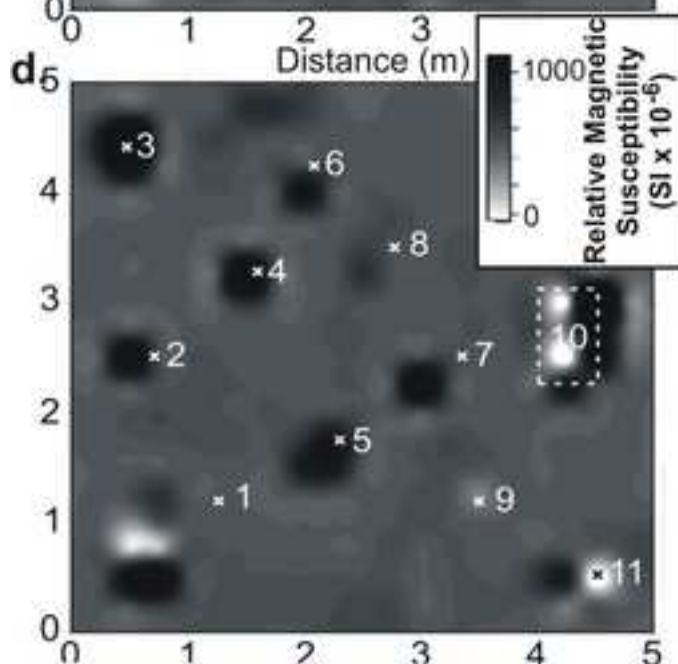


Figure5  
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a.



b.

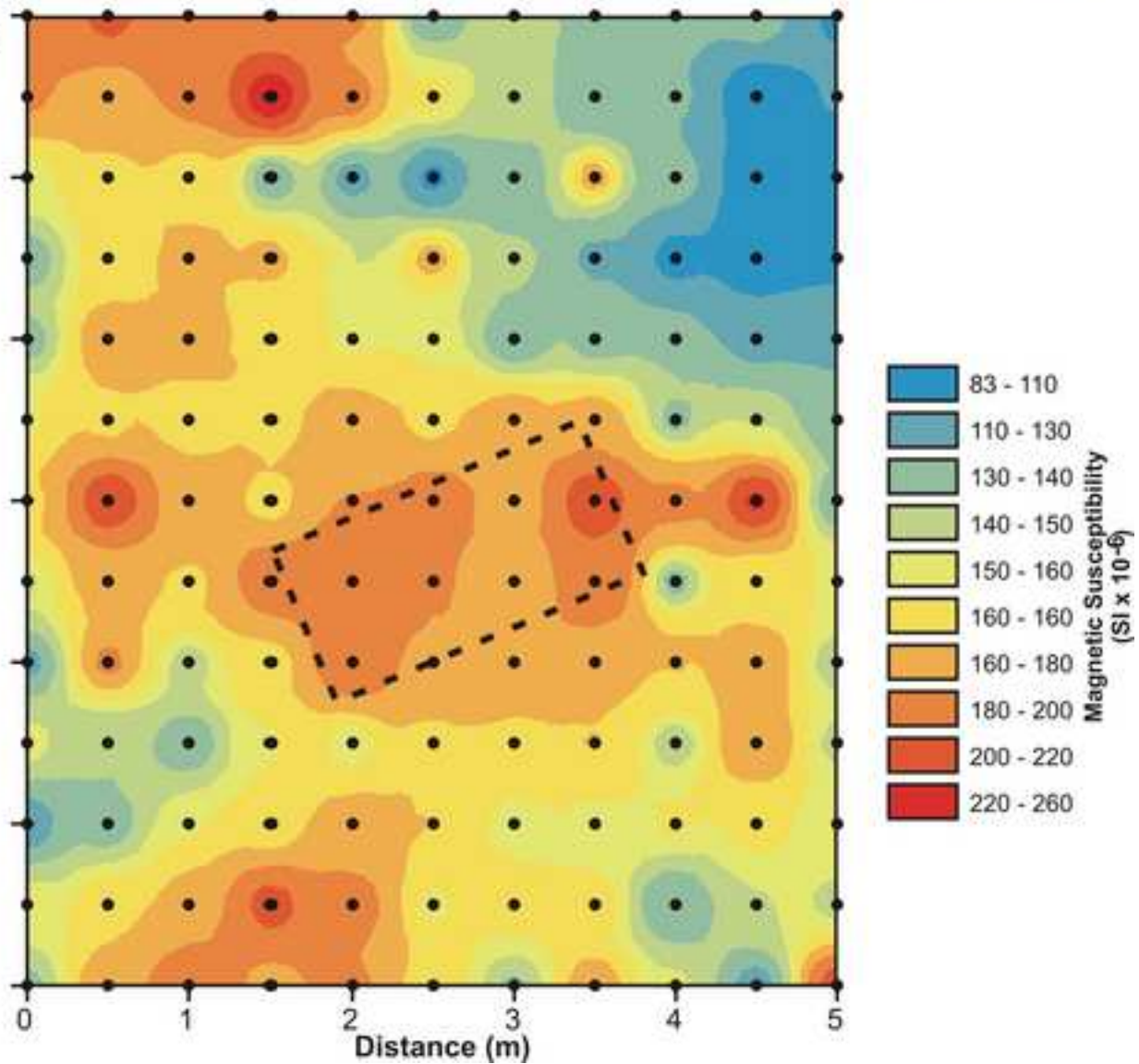
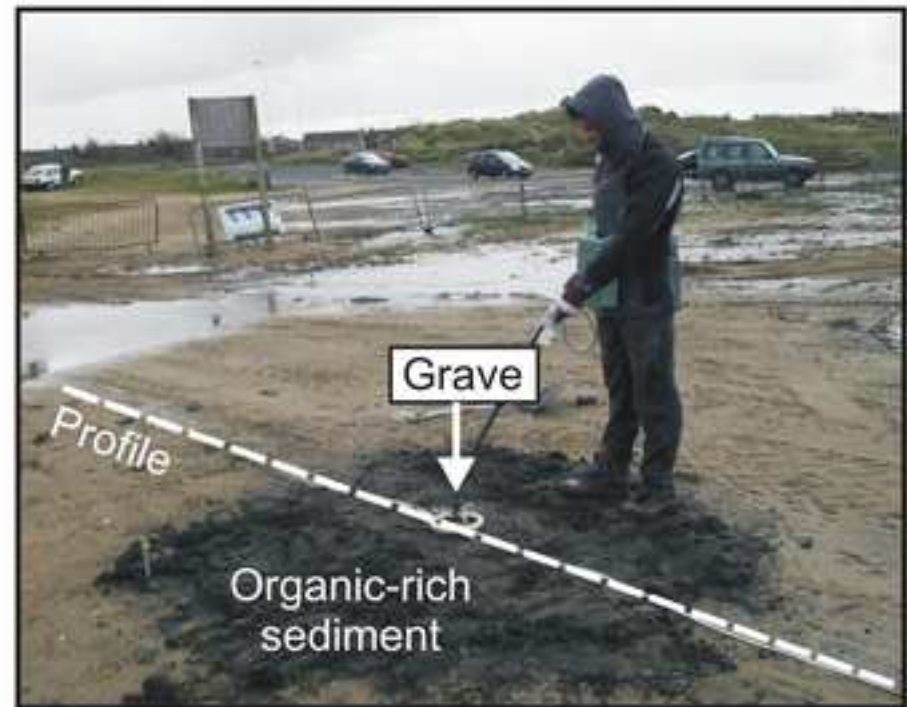


Figure6  
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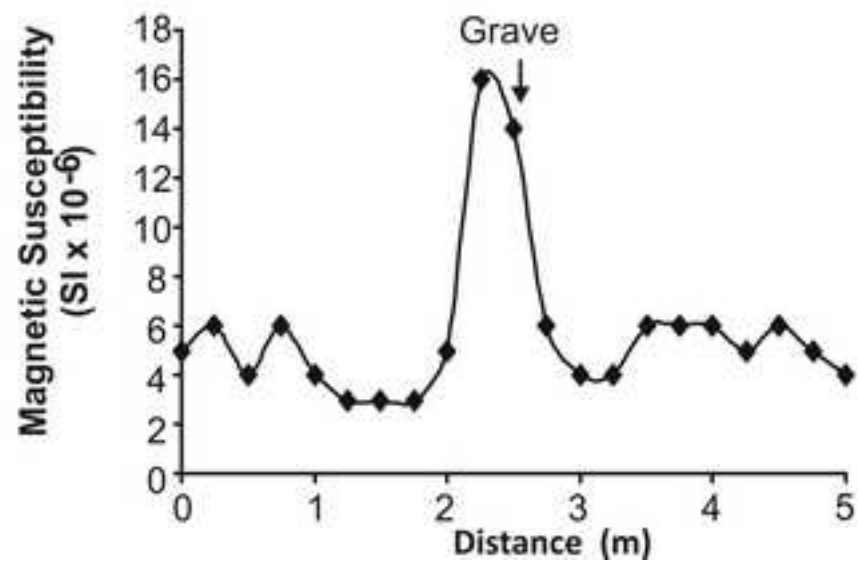
a.



c.



b.



d.

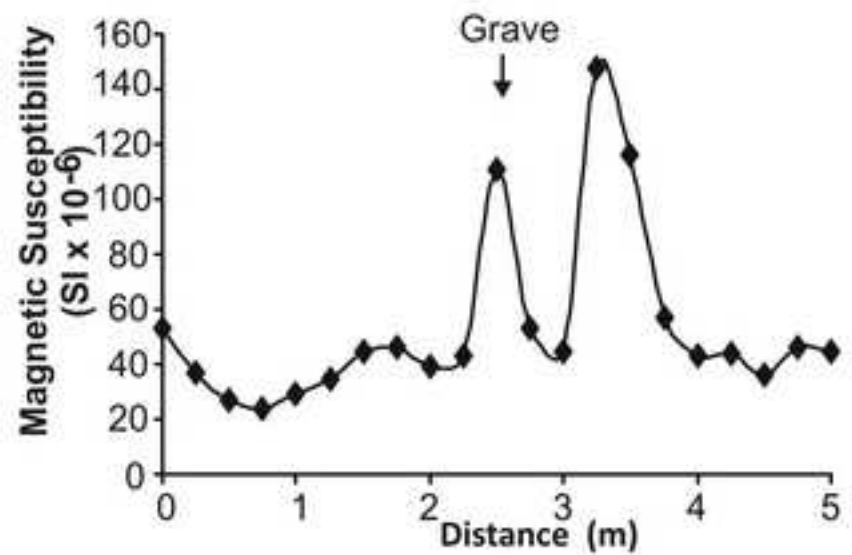


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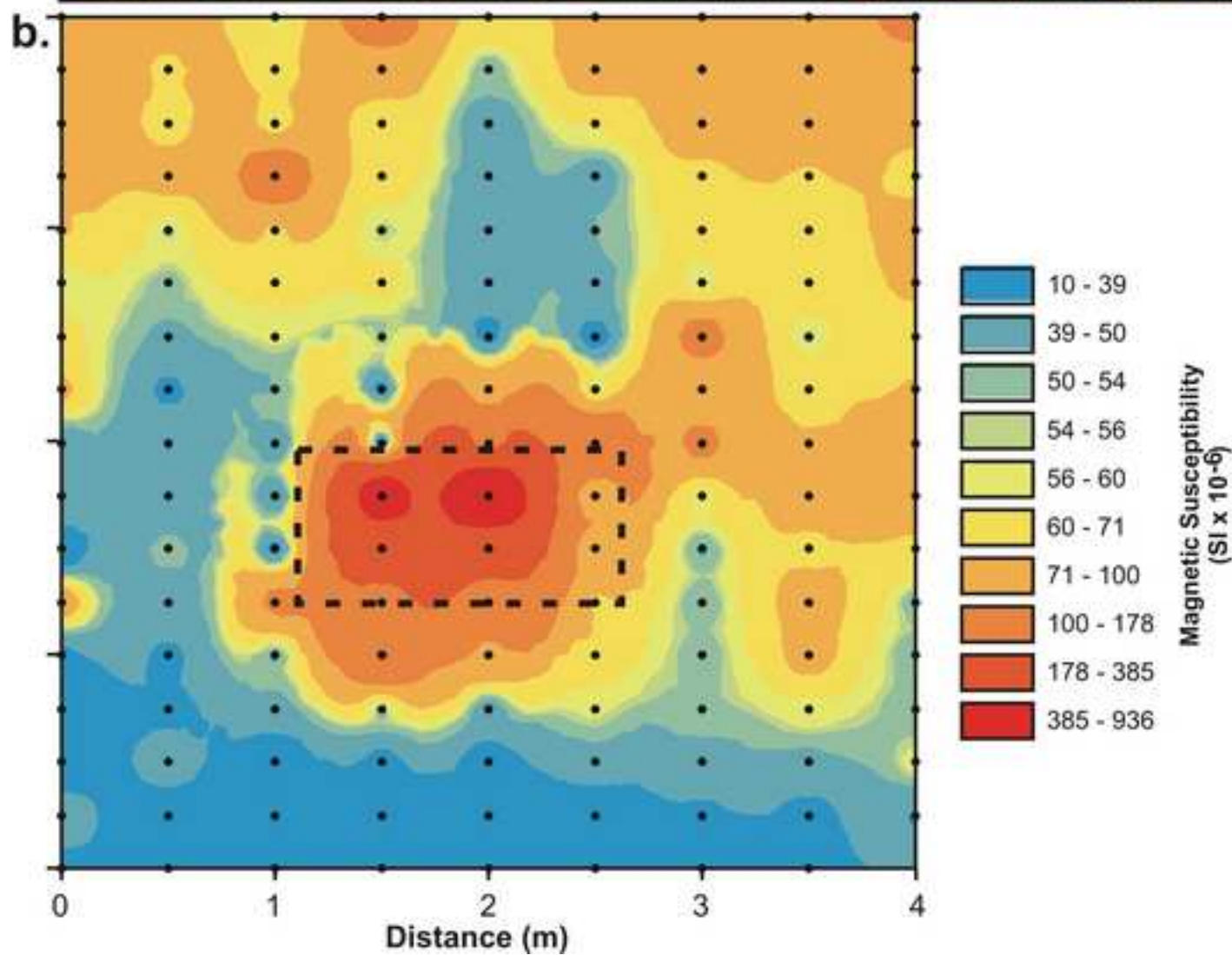
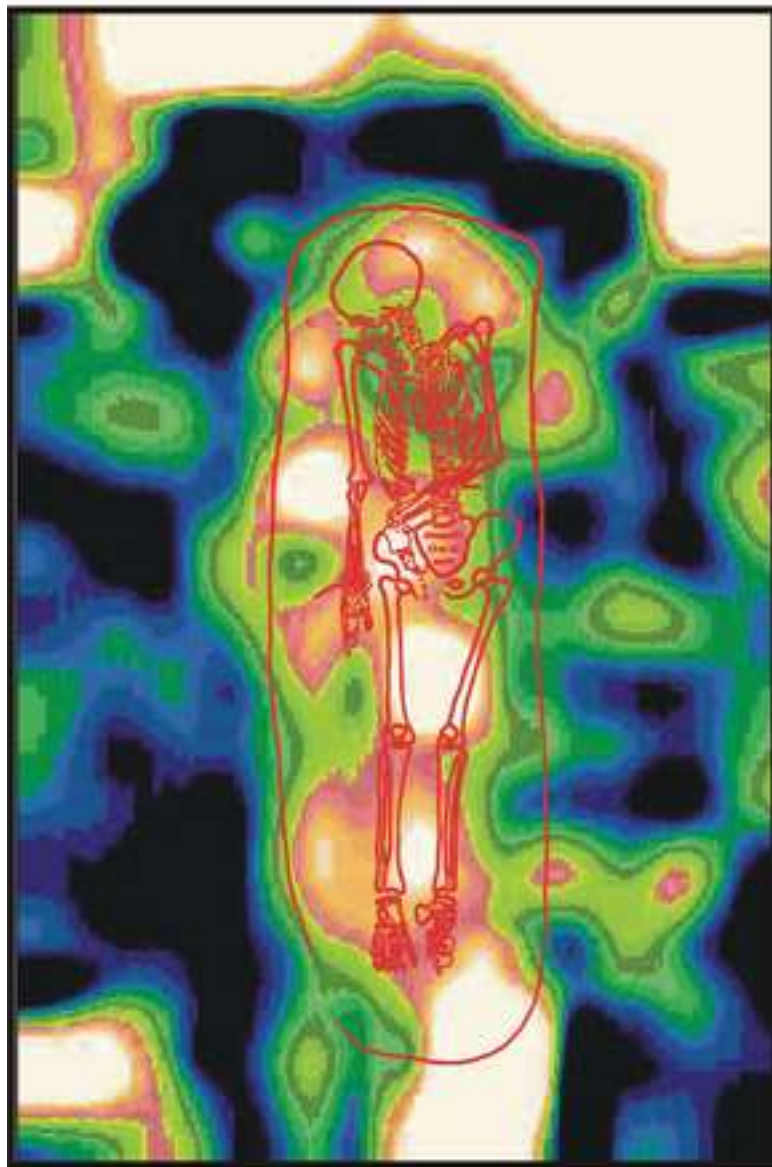


Figure8  
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a.



b.

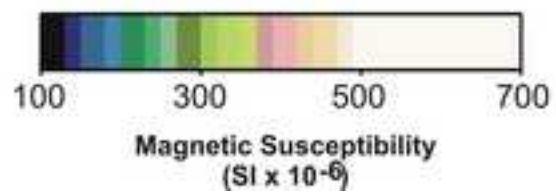




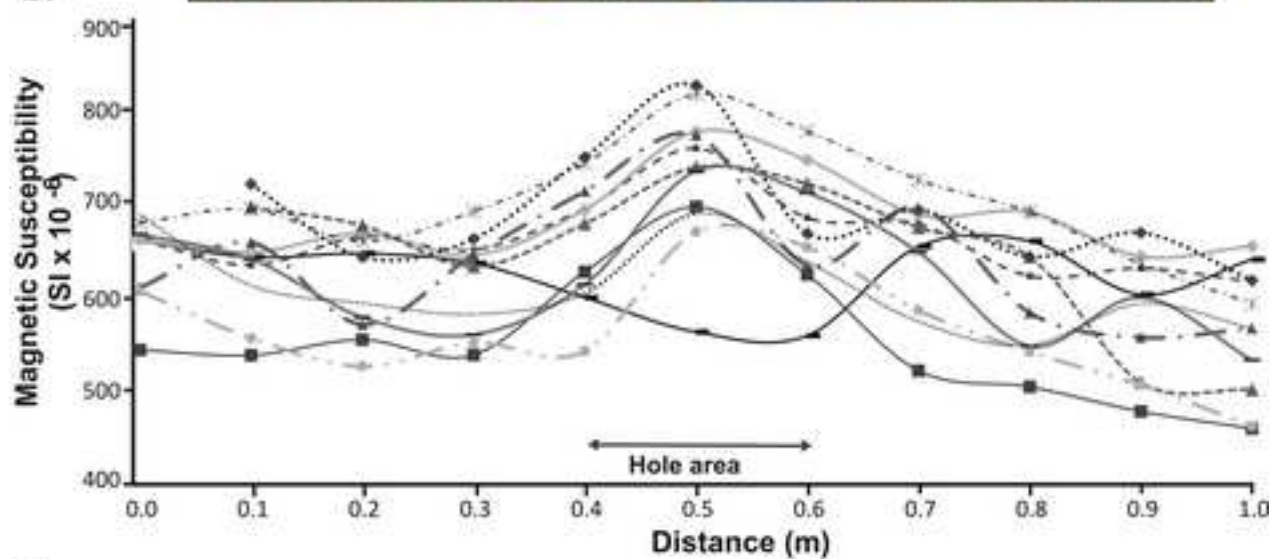
Figure2

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a.



b.



c.

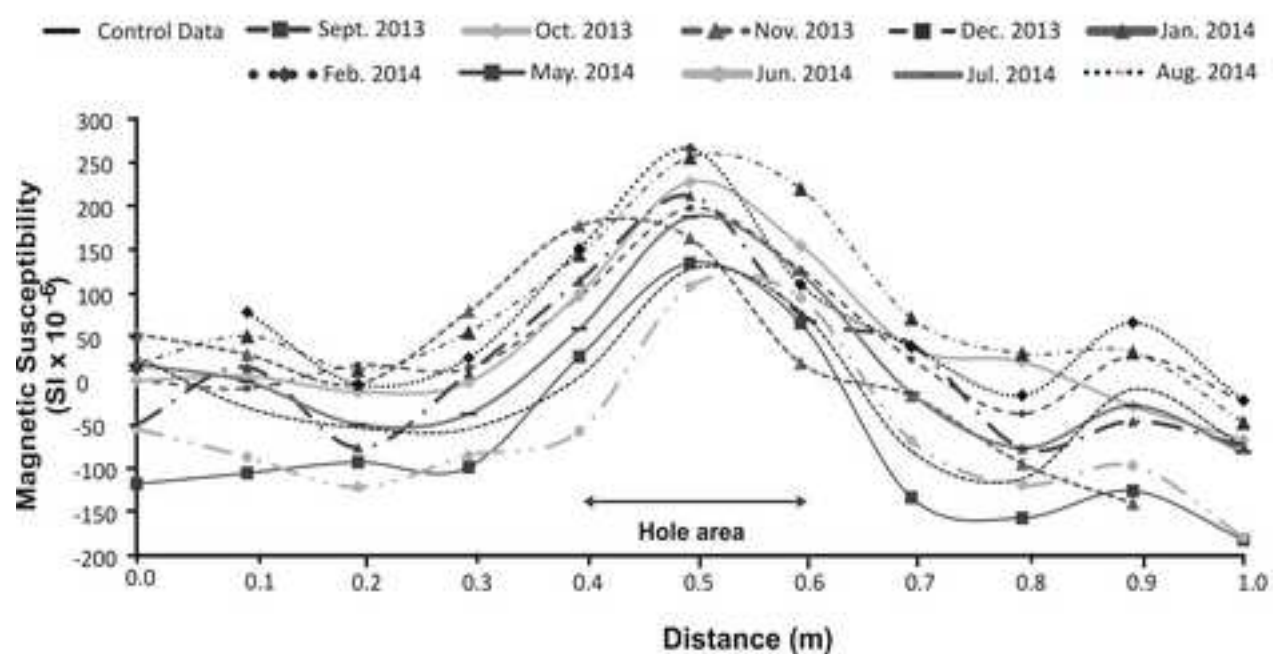
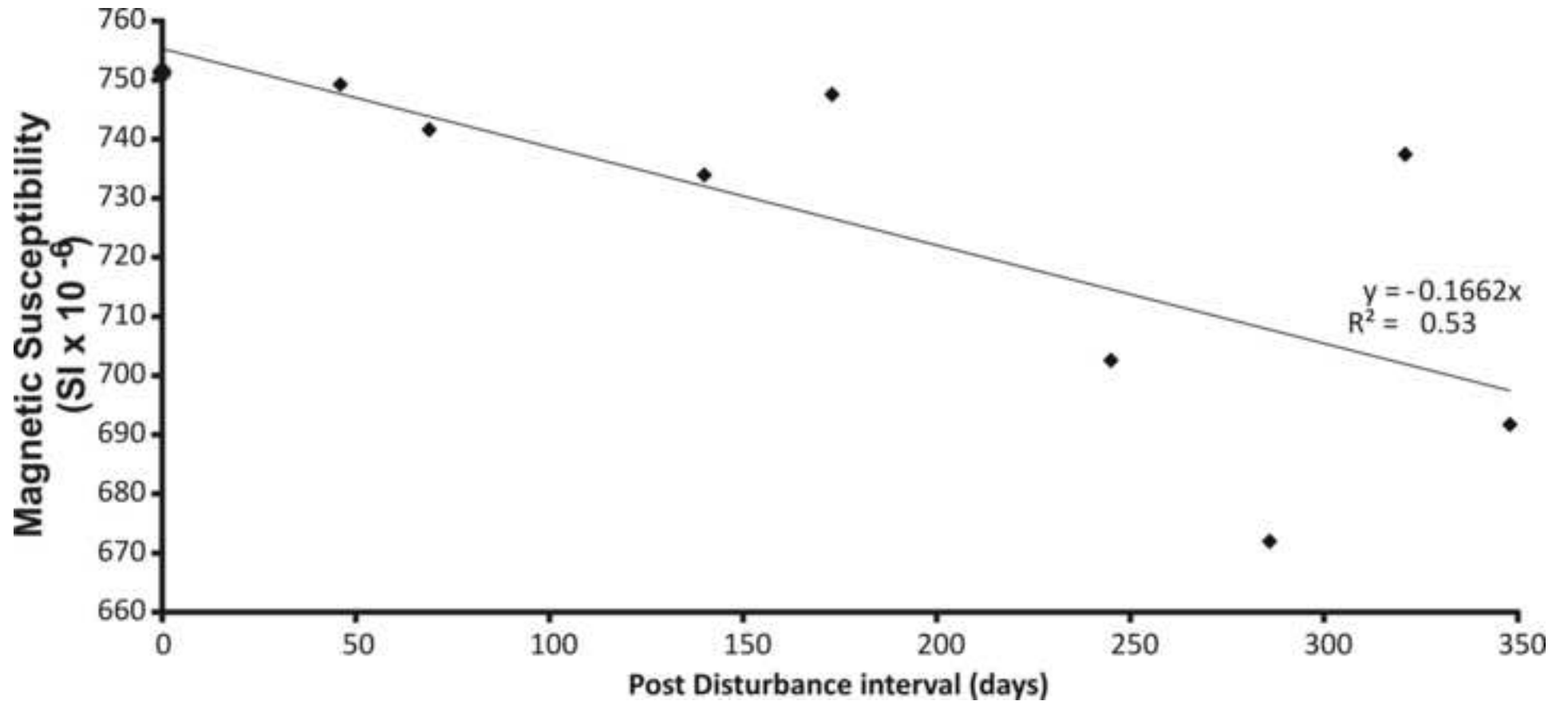


Figure9  
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<b>Target(s)</b>	<b>Post-burial date</b>	<b>Soil type</b>	<b>Depositional environment</b>	<b>Sample spacing (m)</b>	<b>Further Info.</b>
Monitoring disturbed ground (2.2)	0 – 1 year	Sandy loam	Semi-rural	0.1	N/A
Burnt clothes on surface & 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 (2.5)	grave 1 month	Made-ground clay rich	Urban	0.5 x 0.5	[39]
Clandestine (2.6)	grave 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 (2.8)	grave 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.

Target(s)	Near-Surface Geophysics						
	Soil type: sand   clay	Seis- mology /	Cond- uctivity	Resist- ivity	GPR	Mag- netics	Metal detector
Unmarked grave(s)			●	●			●
Clandestine grave(s)			●	●	●		●
UXOs/ IEDs			●	●	●	●	●
Weapons					●	●	●
Drug / cash dumps							●
Illegal waste	●	●	●	●		●	
<b>Common depositional environment</b>							
Woods	○		○	○	●	●	●
Rural	●	●	●	●	●	●	●
Urban		○	○		○		○
Coastal	●	○		○	●	●	●

**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.