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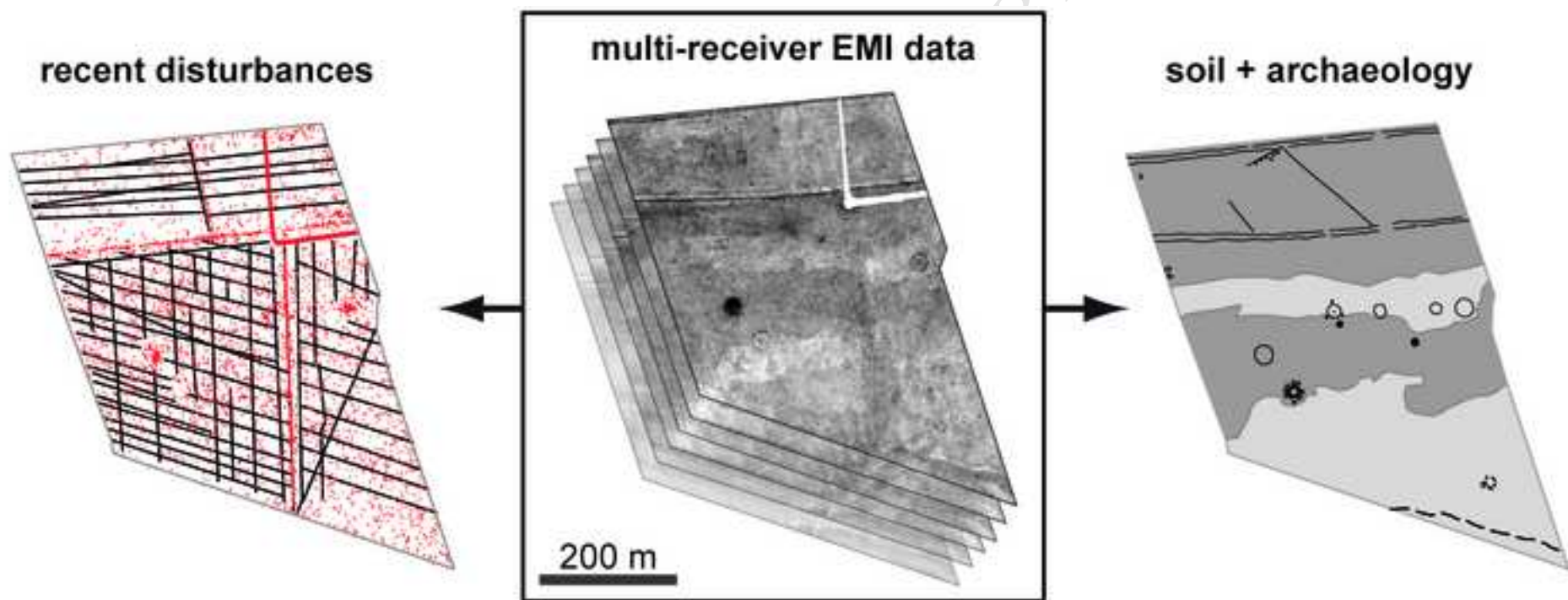
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- Multi-receiver EMI survey was conducted over a 22 ha area near Stonehenge
- We developed a procedure to remove magnetic debris influence from EMI data
- Magnetic noise removal allowed a straightforward discrimination of archaeology
- Multi-layer EMI data allow discerning soil disturbance and ploughed-out archaeology
- EMI offers novel insight into Stonehenge archaeology, pedology and palaeotopography

ACCEPTED MANUSCRIPT

1 **Unveiling the prehistoric landscape at Stonehenge through multi-receiver EMI**

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19 **Abstract**

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2
3 20 Archaeological research at Stonehenge (UK) is increasingly aimed at understanding the dynamic of
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5 21 the wider archaeological landscape. Through the application of state-of-the-art geophysical
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7 22 techniques, unprecedented insight is being gathered into the buried archaeological features of the
8
9 23 area. However, applied survey techniques have rarely targeted natural soil variation, and the detailed
10
11 24 knowledge of the palaeotopography is consequently less complete. In addition, metallic topsoil debris,
12
13 25 scattered over different parts of the Stonehenge landscape, often impacts the interpretation of
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15 26 geophysical datasets. The research presented here demonstrates how a single multi-receiver
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17 27 electromagnetic induction (EMI) survey, conducted over a 22 ha area within the Stonehenge
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19 28 landscape, offers detailed insight into natural and anthropogenic soil variation at Stonehenge. The soil
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21 29 variations that were detected through recording the electrical and magnetic soil variability, shed light
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23 30 on the genesis of the landscape, and allow for a better definition of potential palaeoenvironmental and
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25 31 archaeological sampling locations. Based on the multi-layered dataset, a procedure was developed to
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27 32 remove the influence of topsoil metal from the survey data, which enabled a more straightforward
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29 33 identification of the detected archaeology. The results provide a robust basis for further
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31 34 geoarchaeological research, while potential to differentiate between modern soil disturbances and the
32
33 35 underlying sub-surface variations can help in solving conservation and management issues. Through
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35 36 expanding this approach over the wider area, we aim at a fuller understanding of the human-
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37 37 landscape interactions that have shaped the Stonehenge landscape.

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38 1. Introduction

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3 39 The archaeological landscape of the Stonehenge (UK) results from at least 12 000 years of human
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5 40 occupation, during which prehistoric societies transformed the area into a ritual landscape. An
6
7 41 abundance of prehistoric monuments, with the standing stone monument as the most iconic example,
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9 42 are distributed over approximately 25 km² and are witness to such prehistoric human-landscape
10
11 43 interactions. Human action continues to influence this archaeological complex, with notable examples
12
13 44 including the militarisation of the wider area starting in the end of the 19th century, along with
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15 45 conservation and management measures, and the designation of Stonehenge as a UNESCO World
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17 46 Heritage Site (WHS) (ICOMOS, 1986).

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19
20 47 Stonehenge has attracted research interest from scholars over centuries (Darvill, 2006) and this has
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22 48 made it one of the most investigated archaeological landscapes in the world. Whereas the individual
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24 49 monuments have been the focal point of most early research at the site, landscape archaeological
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26 50 approaches and current research perspectives, such as those set out in the Archaeological Research
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28 51 Framework (Darvill et al., 2005), emphasise the geography and archaeology of the wider area. In line
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30 52 with the status of Stonehenge as a World Heritage Site, this has stimulated a non-invasive approach,
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32 53 and geophysical and remote sensing methods are increasingly being applied to tackle current gaps in
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34 54 knowledge concerning the archaeological landscape. The most recent in a series of research projects
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36 55 is the *Stonehenge Hidden Landscapes Project* (SHLP), which aims to study the archaeological
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38 56 landscape, rather than the individual monuments (Gaffney et al., 2012).

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41 57 Along with other non-invasive mapping using, for example, Light Detection and Ranging (LiDAR)
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43 58 (Bewley et al., 2005; Crutchley, 2002), extensive geophysical surveying significantly enhances our
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45 59 archaeological insight into the Stonehenge landscape (Underhill, 2011). Understanding the detailed
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47 60 pedological variations in the area, however, is less developed. Geological surveys (e.g. Hopson et al.,
48
49 61 2006) have characterized the general stratigraphy of the Salisbury Plain, and soil micromorphological
50
51 62 analyses have supported the identification of prehistoric soil profiles (Macphail and Crowther,
52
53 63 2008). Past research campaigns have already recognized the importance of soil survey at
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55 64 Stonehenge, as some of these have focussed on the detection of colluvial deposits that potentially
56
57 65 seal archaeological features and contain palaeoenvironmental information (Richards, 1990). However,

66 to date only a limited number of depositional environments in the area have been detected and made
67 available for study (Leivers and Moore, 2008).

68 The geology of the Stonehenge landscape consists of Upper Chalk covered with calcareous drift
69 deposits, loess and occasional clay-with-flint patches (Canti et al., 2013; Richards, 1990). On top of
70 these sediments the most widely present soil types are rendzinas, and silty soils with occasional clay
71 enrichment (argillic brown earths and brown calcareous earths (Richards, 1990)). In these well drained
72 soils the preservation of sealed or waterlogged deposits is scarce (French, 2003), and within WHS the
73 soil depth is generally limited. This makes locating colluvial deposits and deeper soil profiles a
74 methodological challenge, but essential to further understanding of the prehistoric Stonehenge
75 environment.

76 The more recent land-use at Stonehenge poses a specific set of problems when working with
77 geophysical survey data from the site. In large areas of the landscape, military activities, mainly dating
78 to the first half of the twentieth century, have significantly disturbed the soil. From firing ranges to the
79 Stonehenge Down airfield south east of Stonehenge, these activities have left behind a large amount
80 of metal debris in the soil that can 'pollute' geophysical data (Darvill et al., 2013; Gaffney et al., 2012).
81 Additional magnetic material left behind during music festivals that took place in the 1970's and -80's,
82 further contributes to such noise in geophysical data (Darvill et al., 2013).

83 To respond to these site-specific issues, we propose to carry out area-wide multi-receiver
84 electromagnetic induction (EMI) survey across of the Stonehenge landscape. While small scale tests
85 with EMI instruments have been conducted over individual monuments at Stonehenge (Bonsall et al.,
86 2013; Gaffney et al., 2012), large-area EMI survey has not yet been taken undertaken. Through
87 advances in soil science and proximal soil sensing (Rossel et al., 2010), EMI sensors have become a
88 very effective tool for mapping soil variation by recording the soil apparent electrical conductivity (σ_a)
89 (Corwin and Lesch, 2005; Rhoades et al., 1976; Sudduth et al., 2005). The strong relationship
90 between σ_a and soil texture is of particular interest as it allows the creation of detailed soil maps based
91 on EMI data (Saey et al., 2009a). At Stonehenge, this use of geophysical soil mapping can help
92 provide the detailed information needed to reconstruct the palaeotopography of the area, and pinpoint
93 both palaeoenvironmental and archaeological sampling locations.

94 Whereas the main geophysical survey techniques that are used in archaeology (magnetometry,
1 95 electrical resistivity and ground penetrating radar (GPR)) each target only one specific variable, EMI
2
3 96 offers the potential to measure both σ_a and apparent magnetic susceptibility (κ_a) simultaneously. This
4
5 97 combined registration of different physical soil variables allows broad insight into the anthropogenic
6
7 98 and natural soil variations, thus facilitating an integral geoarchaeological reconstruction (e.g. De
8
9 99 Smedt et al., 2013a). Multi-receiver EMI soil sensors further add the potential to discriminate changes
10
11 100 in σ_a and κ_a in three dimensions by simultaneously measuring multiple soil volumes (Saey et al.,
12
13 101 2009b). This has already enabled the visualization of vertical σ_a -variations to reconstruct past
14
15 102 landforms (De Smedt et al., 2013b; Saey et al., 2008) and past human environments (De Smedt et al.,
16
17 103 2013c).

20
21 104 In September 2012, a multi-receiver EMI survey was undertaken to evaluate the technique's potential
22
23 105 for mapping anthropogenic and natural subsurface variations within the Stonehenge landscape. An
24
25 106 area of 22 ha was selected near the western extent of the Stonehenge Cursus, where in the 1970s
26
27 107 and 1980s camps were positioned for Stonehenge Free music festival (Fig. 1). The magnetic debris
28
29 108 from these festivals leaves magnetometry data plots peppered with small metallic anomalies that limit
30
31 109 the archaeological interpretation of the images (Darvill et al., 2013; Gaffney et al., 2012). While the use
32
33 110 of a multi-receiver instrument offers insight into the lateral and vertical soil variability, we further
34
35 111 examined how the multi-layered EMI dataset can aid in discriminating between recent topsoil debris
36
37 112 and the underlying archaeology. The presented research forms the start of a large-scale EMI mapping
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39 113 programme at Stonehenge, whereby a core area of 2.5 km² will be surveyed with multi-receiver EMI
40
41 114 over the course of the next three years. In this paper, we present the first survey results with particular
42
43 115 focus on the soil variation and the potential to discriminate recent disturbances from the underlying
44
45 116 archaeology in the study area.

51 118 **2. Multi-receiver electromagnetic induction**

53 119 *2.1 Instrumentation*

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55
56 120 We used a multi-receiver EMI instrument that combines one transmitter coil with four receiver coils
57
58 121 that simultaneously record the soil σ_a and κ_a (Dualem-21S, Dualem, Canada). The receiver coils are
59
60 122 placed in two orientations (horizontal coplanar (HCP) and perpendicular (PRP)) at both 1 m and 2 m

123 from the transmitter (Simpson et al., 2009). Through using different coil orientations with the same
124 intercoil separation different parts of the medium under study can be targeted. When measuring the
125 soil σ_a , a PRP coil configuration with an intercoil separation of 1 m, will obtain most influence from the
126 upper 30 cm of the measured medium. On the other hand, measuring σ_a with a HCP coil pair with the
127 same intercoil separation, the upper part of the medium will affect the recorded signal response in a
128 different manner (McNeill, 1980; Wait, 1962).

129 While the coil orientation mainly influences the shape of the soil volume that is taken into account, the
130 separation between transmitter and receiver coil influences the size of the measured soil volume. For
131 σ_a , a HCP coil pair with a 1 m intercoil separation has a depth of investigation (DOI, defined as the
132 70% response depth) of 1.5 m, an intercoil separation of 2 m increases the DOI of such a coil pair
133 down to 3.2 m below the sensor (Saey et al. 2009b). The depth response of the EMI signal differs for
134 the quadrature-phase signal response (representative for the σ_a) and the in-phase signal response
135 (proportional to the soil κ_a), resulting in κ_a data that representative for a differently shaped soil volume
136 than σ_a data of the same coil pair (De Smedt et al., 2014; Simpson et al., 2010). Furthermore, in most
137 field conditions the κ_a data from PRP coil pairs suffer from high-frequency noise, making them difficult
138 to interpret (De Smedt et al., 2014). For this reason, the PRP κ_a data have not been used in this study.
139 The EMI survey thus results in a six-layered dataset where the maximum depth penetration of the σ_a
140 measurements reaches 3.2 m below the sensor, while the HCP κ_a measurements have maximum
141 depth response of approximately 1.5 m below the sensor.

142 *2.2 Survey strategy and data processing*

143 The study area (Fig. 1) was surveyed between the 17th and 21st of September 2012, using a mobile
144 configuration, whereby the EMI sensor was towed behind a quad bike. The use of a differential GPS
145 (dGPS) with an accuracy ≤ 10 cm allowed for real-time georeferencing, and for the registration of the
146 terrain elevation. EMI measurements were taken along parallel lines, 1.2 m apart and driven in
147 alternating directions, with one sampling cycle every 0.25 m. With this sampling resolution larger
148 archaeological features were targeted, along with the small-scale pedological and geomorphological
149 variations. Each day, soil temperature was recorded at 30 cm below the surface to account for
150 temperature differences in the σ_a data between survey days (Slavich and Petterson, 1990). Before
151 every survey, a calibration line was driven across the area to correct for potential measurement drift

152 following Simpson et al. (2009). In a final step, ordinary kriging (Goovaerts, 1997) was performed to
153 interpolate the survey data to 0.1 m by 0.1 m raster images.

154

155 3 Survey results

156 3.1 Filtering out metallic topsoil debris

157 As in published magnetometry datasets from the area (Darvill et al., 2013; Gaffney et al., 2012), a
158 large amount of local spatial data outliers occur in the EMI data, which are mainly caused by magnetic
159 debris related to the refuse left behind during the 1970s-80s music festivals (Fig. 2a). The objects
160 causing such anomalies are primarily located in the topsoil, producing a widespread and identifiable
161 signature in the in the EMI data. Their influence on the measurements from the four coil
162 configurations, however, differs significantly. In Fig. 3 the EMI measurements are compared for one of
163 the outliers. Note how the anomaly influences coil pairs with 1 m and 2 m intercoil separation
164 differently. Whereas the anomaly is strongly present in the 1 m PRP and HCP σ_a data (Fig. 3a, c), its
165 influence is negligible in the 2 m PRP and HCP data (Fig. 3c). For the κ_a data, the same effect can be
166 seen (Fig. 3d). However, while such an anomaly causes extreme values in the σ_a data (e.g. strongly
167 negative in the 1 m HCP σ_a data (Fig. 2 and 3), these represent local spatial outliers in the κ_a data,
168 which are often situated within the normal measurement range. As features that have been cut into the
169 soil (e.g. pits) have the same spatial extent as the metal-induced anomalies, the use of spatial filters to
170 reduce outlier influence such as median filtering (Scollar et al., 1990) carries the risk of removing
171 archaeological data from the measurements.

172 *Fig. 2 near here*

173 *Fig. 3 near here*

174 To reduce the influence of topsoil metal on the κ_a data, the location of the metal anomalies was
175 therefore deduced from the σ_a data. In the 1m HCP σ_a data layer, the influence of the topsoil debris is
176 the most prominent, resulting in a strongly negative signal response (Fig. 3a, c). Near larger metal
177 objects, strongly positive σ_a values were recorded. Within the low conductive environment at
178 Stonehenge, the high σ_a values can be identified as the upper 1% percentile of the 1HCP σ_a data
179 values (i.e. above 9.2 mS/m, ranging up to 312.3 mS/m). By extracting these data points along with

180 negative data from the 1 m HCP σ_a measurements, a map of the metal scatter was produced (Fig. 2b).

181 With this information, the influence from the metallic topsoil contamination was removed from the κ_a

182 data layers by discarding the measurements made on the identified locations. To account for the

183 different spatial sensitivity from the 2 m HCP coil pair, rendering a wider influence of the detected

184 metallic anomalies, a filter buffer of 1 m was taken into account around the identified metal objects

185 (Fig. 4). To diminish the metal effect on the σ_a data, the same procedure was applied to the σ_a data

186 layers. The presented data in the following sections have all been filtered following this procedure, and

187 were subsequently interpolated to 0.1 by 0.1 m rasters through ordinary kriging (Goovaerts, 1997).

188 The resulting data plots offered a more straightforward insight into the archaeological and natural

189 subsoil variations, and allowed a clearer visualization of the detected archaeological features. As an

190 example, Fig. 5 compares the 2 m HCP κ_a data from a hengiform monument, detected through the

191 SHLP (Gaffney et al., 2012) before and after metal removal. The filtered data (Fig. 5b) allow a

192 straightforward delineation of the different parts of the monument as the shape of the large circle of

193 pits is more clearly defined (see for example the influence of the outliers indicated by arrow 1 on Fig.

194 5a). Near the south-western entrance of the monument, another large anomaly was identified as a

195 metal-induced outlier (Fig. 5a, arrow 2). On the west of the monument, a group of anomalies remained

196 present in the filtered dataset, indicating a possible archaeological origin (Fig. 5b). (For comparative

197 purposes, all σ_a and κ_a data sets have been made available in pdf-format as online supplementary

198 data.)

199 *Fig. 4 near here*

200 *Fig. 5 near here*

201 3.2 Natural soil variation and modern soil disturbance

202 The natural subsurface variations are most clearly visible in the 2 m PRP σ_a data, representing a soil

203 volume between 0 m – 1 m below the sensor, indicating that most variability is situated within this

204 depth range. As σ_a informs mainly on soil texture (Saey et al. 2009a), the variations seen here can be

205 attributed to the depth of the shallow chalk bedrock, visible as resistive zones, and the overlying more

206 conductive silty soil. Where soil thickness increases, a higher σ_a is attested. Most prominent is the

207 broad band of low σ_a values running east-west through the area, indicating a shallow chalk ridge (A on

208 Fig. 6a). In the south, low σ_a values also show shallow bedrock, but here an irregular pattern of high

209 and low conductivities further indicates chalk weathering patterns and the infilling of cracks and
1 210 depressions in the chalk bedrock with more conductive soil. In addition to the large-scale variability,
2 211 two circular anomalies were detected inside the Cursus (B on Fig. 6a). These were identified as the
3
4 212 subsurface expression of naturally formed rings of grassland fungi ('fairy rings') resulting in a
5
6 213 detectable increase in soil organic matter content or aggregate formation.
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11 214 *Fig. 6 near here*
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14 215 The chalk morphology and soil variation have almost no influence in the κ_a data. However, in the south
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16 216 of the study area, a band of increased magnetic susceptibility indicates magnetic sediments that are
17
18 217 likely related to accumulated organic matter (C on Fig. 6b). The topographical position of this anomaly
19
20 218 points to a fluvial origin, suggesting that these sediments are organic enriched palaeochannel
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22 219 infillings.
23

24
25 220 The κ_a data further show the impact of modern land-use on the preservation of the Stonehenge
26
27 221 heritage. Numerous lines run in an east-west and north-south direction through the area, some of
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29 222 which were already located through Ordnance Survey maps and historical aerial photography (Amadio
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31 223 and Bishop, 2010), and most likely testify of former ploughing and field drains. These mainly seem to
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33 224 affect the subsurface archaeology as the lines do not cross the monuments that remain present above
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35 225 ground level.
36

37 38 226 3.3 Archaeology 39

40
41 227 Anomalies indicating archaeological features are attested in both the σ_a and κ_a data, and can be
42
43 228 discerned the clearest in the 1 m PRP σ_a and 2 m HCP κ_a measurements (Fig. 7). Features that are
44
45 229 most apparent in the σ_a data include the Cursus ditch in the north of the site, and the annular
46
47 230 anomalies related to known crop marks and barrow monuments (Crutchley, 2002; Gaffney et al.,
48
49 231 2012). In the south of the survey area, a number of small conductive anomalies of unknown origin
50
51 232 were detected. However, for some their location suggests a correlation to known monuments (see
52
53 233 below). Within the boundaries of the Cursus, strongly conductive anomalies indicate pits and linear
54
55 234 features (Fig. 6a, Fig. 7a B), a number of which were attested in previous geophysical surveys (Darvill
56
57 235 et al., 2013; Gaffney et al., 2012).
58

59
60 236 *Fig. 7 near here*
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237 The soil perturbations inside the Cursus are clearly visible in the κ_a data, where apart from the various
238 pit-like anomalies (Fig. 6b, Fig. 7b C), the linear traces show as non-magnetic anomalies (Fig. 6b, Fig.
239 7b C). Overall, the κ_a data allow for the most straightforward interpretation of the archaeological
240 variations within the area. The 2 m HCP κ_a data allow the clearest delineation of the detected
241 anomalies. As an example we present the hengiform monument that was detected at monument
242 Amesbury 50 (Fig. 5, Fig. 7b F) (Gaffney et al., 2012). Even with the rather coarse sampling density,
243 the interior structure of the feature can be discerned. Traces of at least one ring of pits can be
244 identified, encircled by a large segmented ditch. Additional variation was detected in the centre of the
245 feature, but further analysis of this variation requires a denser sampling resolution. Throughout the
246 area, the known barrow monuments are clearly defined in the κ_a data. For some, the internal structure
247 becomes apparent, along with smaller features surrounding the monuments. Examples include three
248 small magnetic anomalies around the central barrow (known as Amesbury 49) (Fig. 7b E), and the
249 magnetic anomaly in the middle of the circular barrow ditch.

250 Between the two southernmost barrows two large magnetic anomalies can be seen in alignment with
251 these monuments (Fig. 7b G). As the anomalies occur in several of the EMI datasets (e.g. 1 m HCP σ_a
252 (Fig. 2 a), 1 m HCP κ_a (Fig. 6 b)), these could indicate severely ploughed-out barrows. This hypothesis
253 is supported by the intersection of the westernmost anomaly by one of the linear soil disturbances,
254 which shows that the anomaly predates this modern soil feature.

255 In the south of the study area, a segmented ditch, known as Amesbury 115, shows up as a
256 concentration of highly susceptible anomalies (Fig. 7c). This annular feature, which has been identified
257 in the 1940s through aerial photography (Amadio and Bishop, 2010), can be seen in the κ_a data as a
258 six-segment causewayed ditch.

260 4 Discussion

261 4.1 Discriminating recent soil alterations and metal removal

262 The procedure to remove the signal produced by topsoil metal from the EMI datasets presented here,
263 offers a straightforward means to discriminate between recent metallic topsoil debris and underlying
264 soil variability. This method provides a solution in areas where similar metallic debris is present in the

265 topsoil from recent activities (see for example the issue of metal contamination in green waste
1
2 266 compost raised by former UK environment minister Benyon (Quinault, 2012)), which are often deemed
3
4 267 unsuited for geophysical prospecting due to the large amount of metallic anomalies. At Stonehenge,
5
6 268 the resulting map of the metallic anomalies can be used to improve the discrimination of targeted
7
8 269 features in the magnetometry datasets that are already available (Darvill et al., 2013; Gaffney et al.,
9
10 270 2012). Through combining the topsoil metal locations with the linear modern soil intrusions that were
11
12 271 attested throughout the entire survey area, a map can be produced of the modern subsurface
13
14 272 disturbances (Fig. 8). Such information can then be used in solving site management and
15
16 273 conservation issues.

17
18
19 274 *Fig. 8 near here*

22 275 *4.2 Geoarchaeological soil variation*

23
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25 276 The combined analysis of current elevation and the natural soil variation of the study area (Fig. 9a),
26
27 277 indicates a palaeotopography that differs from the current relief. The central shallow chalk ridge,
28
29 278 bordered in the north and south by thicker layers of silty soil overlying the chalk bedrock, is a witness
30
31 279 to the erosion of overlying silty soil. In the south of the site, the chalk again becomes more dominant
32
33 280 as the steep southern slope boosts soil erosion. At the bottom of this hillside, the palaeochannel
34
35 281 segment further indicates past transportation of runoff and eroded sediments towards the east. This
36
37 282 southern part of the study area is a potential sampling location for deposits harbouring
38
39 283 palaeoenvironmental information. However, coring would be required to verify the hypothesis and
40
41 284 determine the detailed stratigraphy of the feature.

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43
44 285 *Fig. 9 near here*

45
46
47 286 Adding the detected archaeological variation to the soil map allows a preliminary overview of the
48
49 287 geoarchaeological soil variation (Fig. 9b). The most prominently situated features within the area are
50
51 288 the central barrows (Amesbury 48 and 49; A and B on Fig. 9b), with two possible ploughed-out barrow
52
53 289 monuments (Fig. 9b C) aligned between them, following the central chalk ridge and the current
54
55 290 topography. The presence of ploughed-out barrows at these locations is further supported by the slight
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57 291 elevation that was attested at the location of each anomaly. In addition, the existence of one such
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292 feature has already been suggested through the Stonehenge WHS Landscape Project (Amadio and
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2 293 Bishop, 2010).

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4 294 The Cursus ditches and associated banks are recurrent features throughout the EMI data layers (D on
5
6 295 Fig 9b). Through reducing the influence of metal in the EMI survey data, a better distinction could be
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8 296 made between the topsoil noise and anomalies indicating past soil intrusions (pits). The location of the
9
10 297 most characteristic of these pits is shown in Fig. 9b (E). The linear anomalies within the Cursus
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12 298 boundaries (F on Fig. 9) seem to be associated with some of the detected pits and intersect the
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14 299 Cursus bank. However, the origin of these features remains unknown.

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16
17 300 In the southern part of the study area, the combination of σ_a and κ_a data over Amesbury 115 supports
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19 301 the presumed existence of a south-western entrance of the monument (Amadio and Bishop, 2010), as
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21 302 conductive anomalies suggest the presence of associated features adjoining the segmented ditch
22
23 303 (Fig. 9b, G). Through validation of these anomalies and detailed analysis of the bedrock morphology,
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25 304 the presence of a south-eastern entrance for Amesbury 115 could be investigated further. In addition,
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27 305 the presence of the nearby palaeochannel segment could prove to have been instrumental in
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29 306 choosing the location of this monument.

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34 35 308 **5 Conclusions**

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38 309 The results presented here demonstrate how a wealth of information on the past and present soil
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40 310 variations at Stonehenge can be obtained through a single multi-receiver EMI survey. In addition, the
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42 311 methodology to remove the influence of topsoil metal on the EMI data overcame the masking effect of
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44 312 topsoil debris on sub-surface features. This provides a solution to outstanding issues in geophysical
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46 313 surveying within the Stonehenge landscape (Darvill et al. 2013, Gaffney et al. 2012), as this procedure
47
48 314 can be implemented when using or interpreting other geophysical datasets. The multi-layered EMI
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50 315 dataset also enabled discriminating between different types of natural and anthropogenic soil variation
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52 316 within the study area. In this respect, the potential to identify the most significant data layers from this
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54 317 dataset, based on specific research questions, makes multi-receiver EMI a particularly versatile tool in
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56 318 geoarchaeological research. The mapped natural soil variability provides an insight into the
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58 319 palaeotopography of the area, which will facilitate the identification of potential archaeological and
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320 palaeoenvironmental sampling locations. Modern soil disturbances were also identified, along with the
1 321 remnants of flattened earthworks, showing how EMI can contribute to unveiling and managing the
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3 322 archaeology within the Stonehenge landscape. The simultaneous investigation of shallow and deeper
4
5 323 soil layers through a multi-receiver EMI instrument has further allowed for the clearer delineation of
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7 324 archaeological features in the chalkland environment, and emphasises the value of discriminating
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9 325 between different soil volumes.
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12 326 It has been proven that detailed geophysical soil mapping improves our knowledge of the Stonehenge
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14 327 environment, and offers an insight into the genesis of the current landscape. While invasive validation
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16 328 (e.g. coring) remains necessary, the results provide a robust basis for further geoarchaeological
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18 329 research. Through expanding this approach over a wider area, another significant step can be taken
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20 330 towards understanding the complex human-landscape interactions that have shaped the Stonehenge
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22 331 landscape.
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4
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10
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442 **8 Figure captions**

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5 444 **Figure 1:** Satellite image of the core of the Stonehenge World Heritage Site (source: Google Earth, ©
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7 445 2010 Google) with indication of the 22 ha EMI survey area (A), the extent of the Stonehenge
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9 446 Cursus (B) and the Stonehenge monument (C).

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15 448 **Figure 2:** a) σ_a data from the 1 m HCP coil configuration showing numerous negative anomalies
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17 related to metallic topsoil debris, b) location of the metallic topsoil debris based on the 1 m
18 449 HCP σ_a data (Coordinates in meters UTM 30N, WGS 84). The arrows in (a) indicate the
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20 450 anomalies shown in Fig. 3 (arrow 1), and Fig. 4 (arrow 2)
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27 453 **Figure 3:** Comparison of the influence of a metal-induced anomaly on the EMI measurements. The
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29 position of the transect is shown over the 1 m HCP σ_a data (a) and κ_a data (b) plots. In (c) the
30 454 σ_a data from each coil configuration are compared along this transect, d) shows the κ_a data
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32 455 from the 1 m and 2 m HCP coil pairs along the transect. The location of the anomaly is
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34 456 indicated on Fig. 2a (arrow 1).
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41 459 **Figure 4:** Comparison of metal influence removal in the 2 m HCP κ_a data with and without the 1 m
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43 filter buffer. The left column shows the interpolated data, while the column on the right shows
44 460 the individual data points. In a), the original anomaly is shown in the 2 m HCP κ_a data. The
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46 461 filtered 2 m HCP κ_a data without (b) and with (c) implementation of a 1 m filter buffer are
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48 462 shown below. The location of the anomaly is indicated on Fig. 2a (arrow 2), and on Fig. 5
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50 463 (arrow 2).
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467 **Figure 5:** Comparison of the anomalies detected at the hengiform monument (see Gaffney et al.
1 2012) as seen in the 2 m HCP κ_a data before (a) and after (b) metal removal. In (a), two
2 468 anomalies are indicated that were related to the metal topsoil debris, in (b) a group of
3 469 anomalies are indicated that remained present in the filtered data, which suggest the presence
4 470 of pits.
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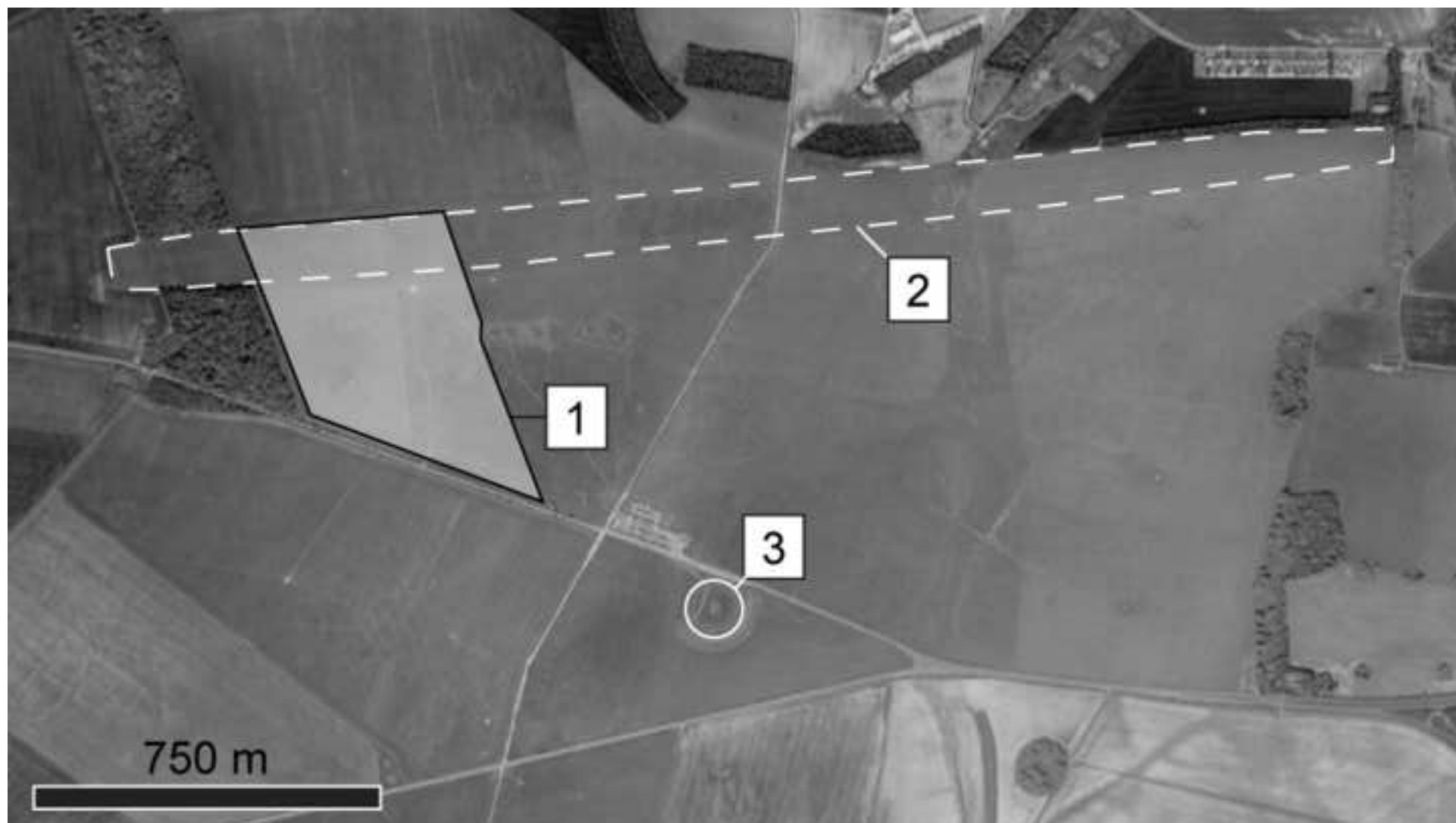
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13 **Figure 6:** The 2 m PRP σ_a data, representative for the soil variation between 0 m – 1 m below the
14 473 sensor (a). The variation shows a central chalk ridge (A) bordered by more conductive soil in
15 474 the north and south. In the north two circular anomalies are indicated (B) that are related to
16 475 grassland fungi. In (b) the 1 m HCP κ_a data are shown, revealing possible palaeochannel
17 476 deposits in the south of the area (C). Further magnetic anomalies include large linear features
18 477 within the boundaries of the Cursus (D), and two circular anomalies that possibly indicate
19 478 ploughed barrow monuments (E).
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31 **Figure 7:** The 1 m PRP σ_a data (a), and the 2 m HCP κ_a data (b) with a detail of the small
32 481 causewayed ditch (Amesbury 115) shown in (c). In (a), apart from the Cursus ditches in the
33 482 north of the area the different barrow monuments can clearly be discriminated in the centre of
34 483 the field. Small conductive anomalies that could be related to archaeology are found in the
35 484 south of the field (A), and within the Cursus boundaries (e.g. B). In (b), the most characteristic
36 485 κ_a -anomalies are; the pit-like anomalies (C) and the linear features (D) detected inside the
37 486 Cursus monument, the annular and round anomalies related to barrow monument Amesbury
38 487 49 (E), two traces of possible ploughed barrows aligned between the known monuments (G)
39 488 and the hengiform monument (F) located at the site of Amesbury 50.
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53 **Figure 8:** Modern soil disturbance and metal contamination within the survey area based on the EMI
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494 **Figure 9: a)** Soil map derived from the σ_a data with indication of the palaeochannel (black dashed line)
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2 495 attested in the κ_a data, and plotted elevation contours (elevation in meters WGS 84). **b)**
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4 496 Overview of the detected geoarchaeological variability, showing the soil variation and the
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6 497 location of the most characteristic anomalies indicating archaeology. These include; known
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8 498 barrow monuments Amesbury 48 (A) and 49 (B), two possible ploughed barrow monuments
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10 499 (C), the Cursus ditches and adjacent banks (D), pits (E) and linear anomalies (F) inside the
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12 500 Cursus, a causewayed ditch and adjoining anomalies near the south-west of the structure (G),
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14 501 several small ditch-like anomalies (H), the hengiform monument at Amesbury 50 (I).

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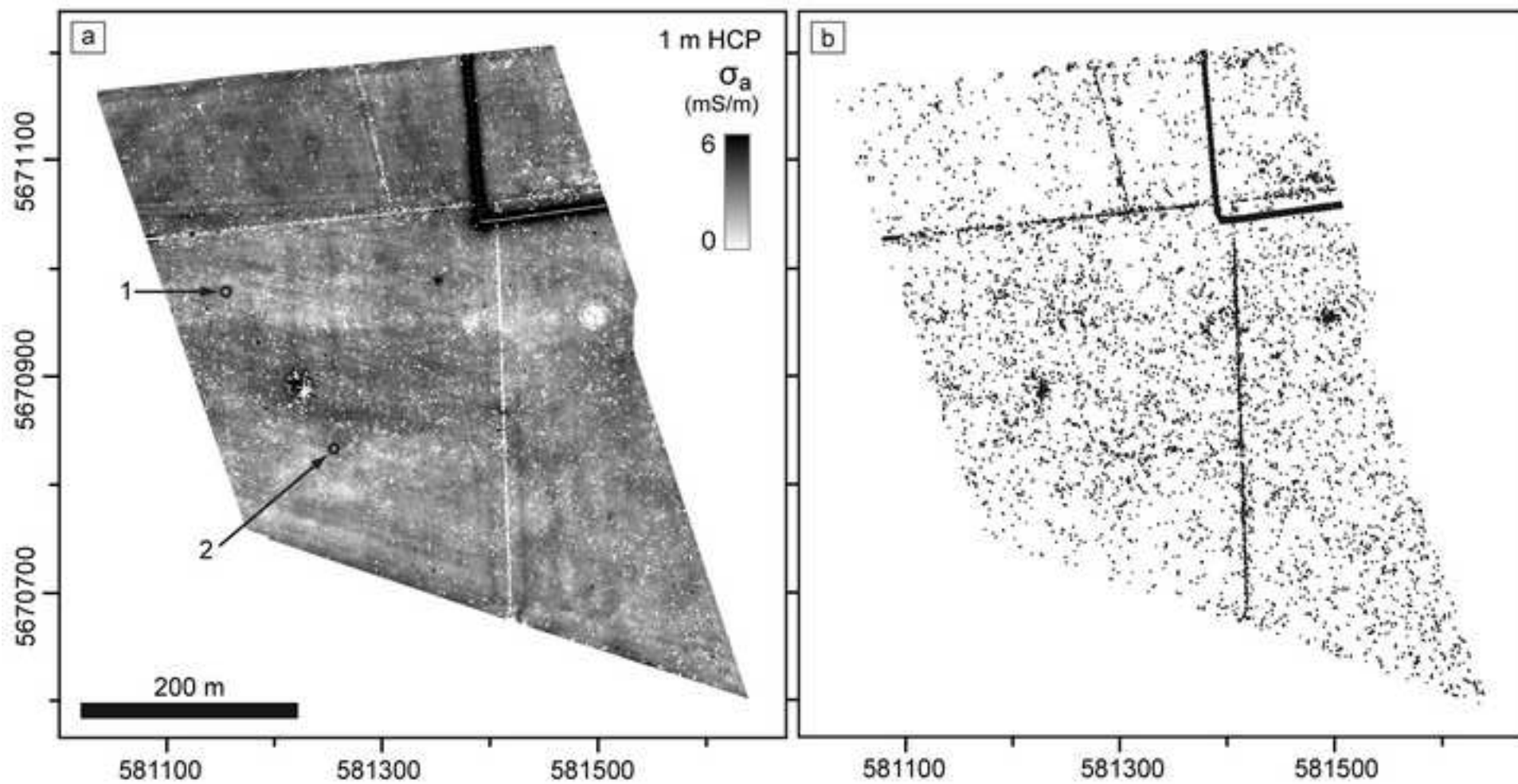
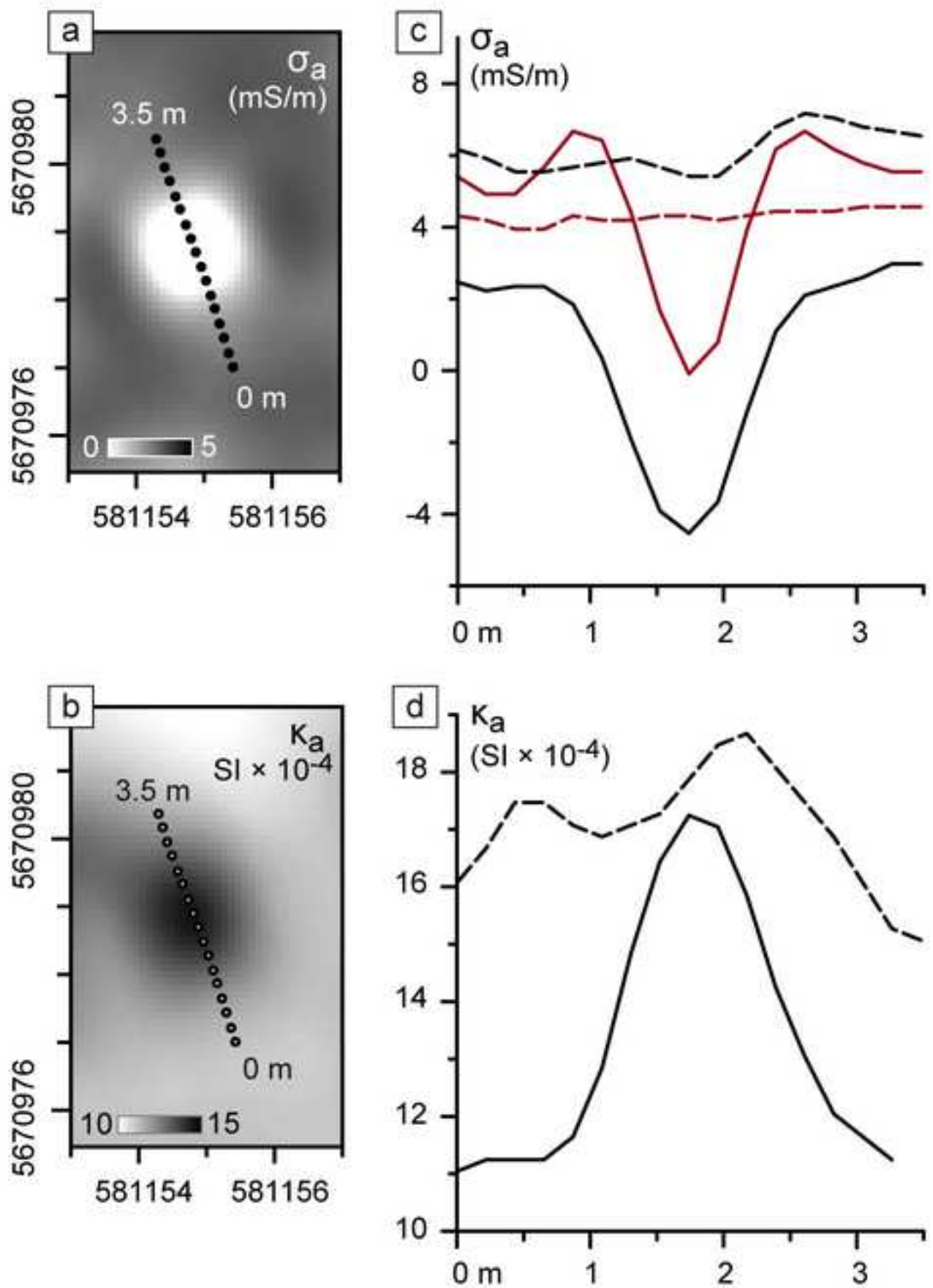
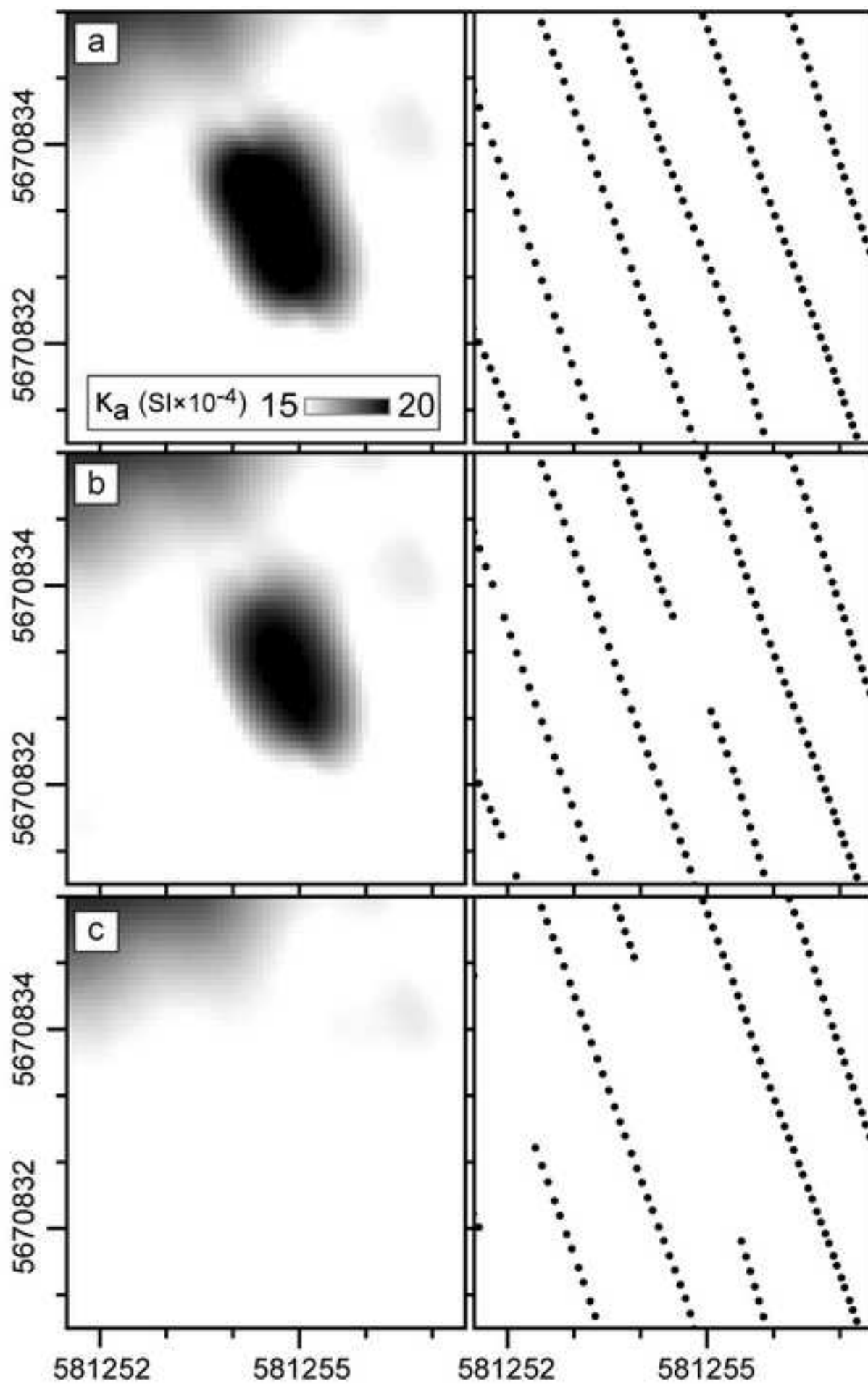


Figure 3

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— 1 m PRP -- 2 m PRP — 1 m HCP -- 2 m HCP

Figure 4



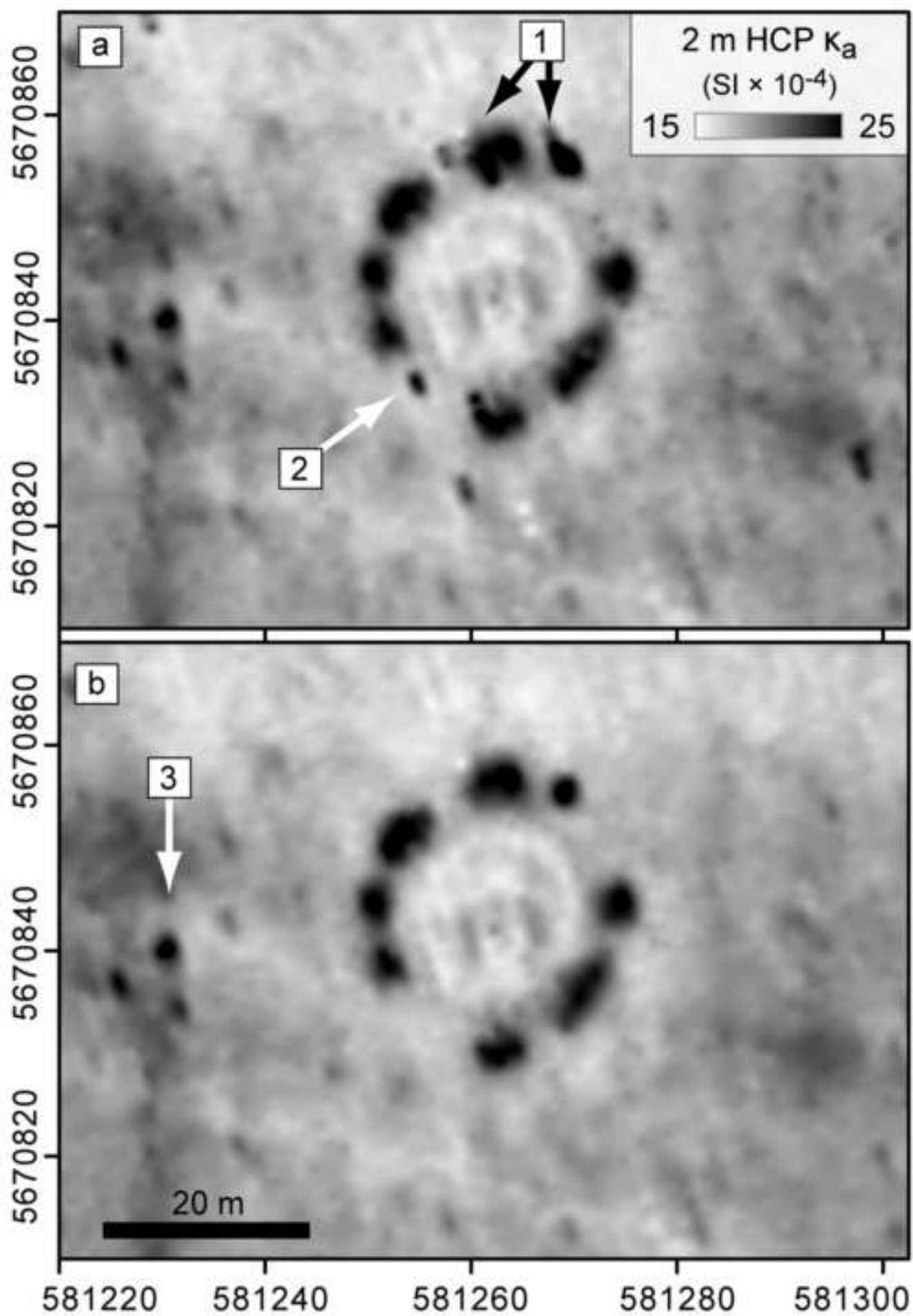


Figure 6

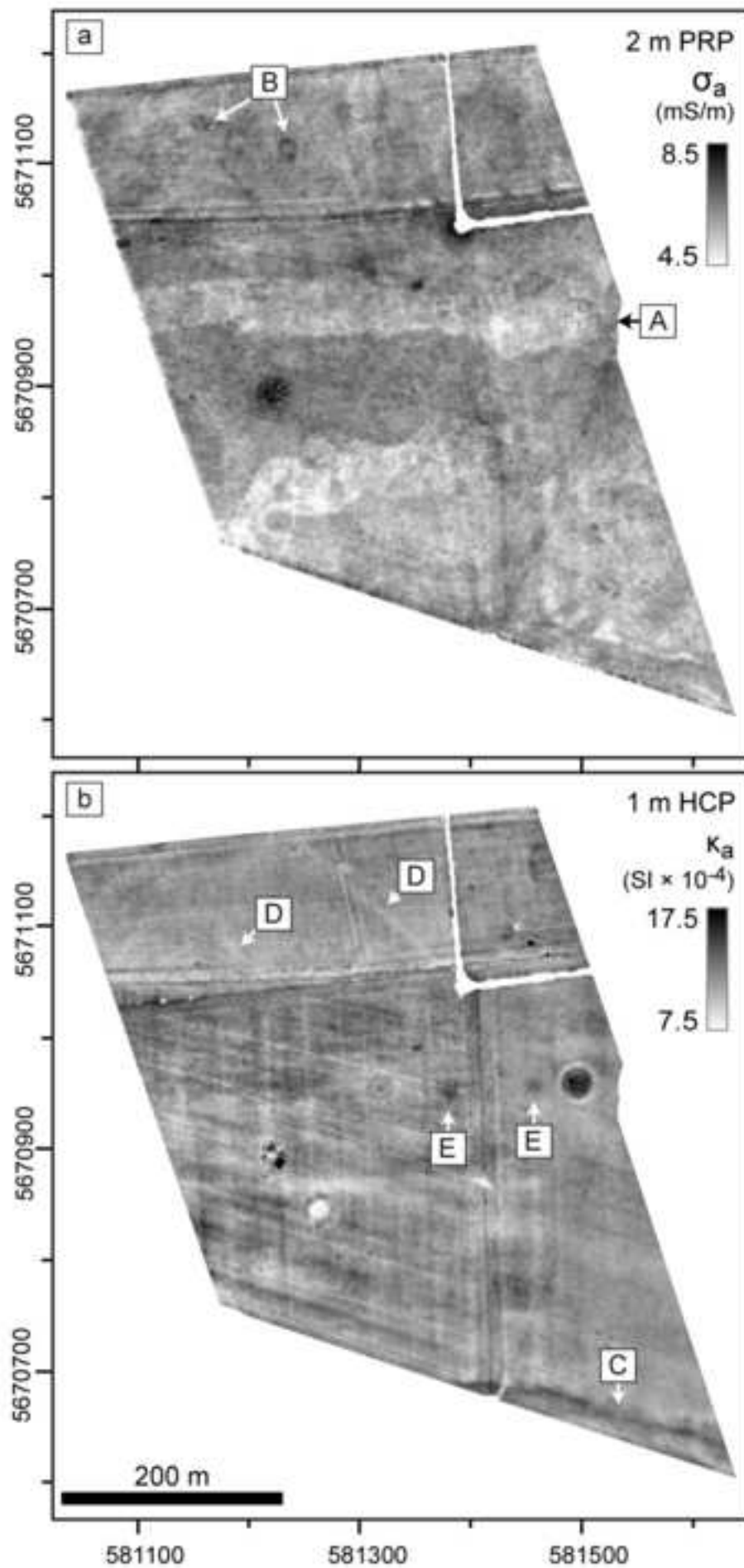


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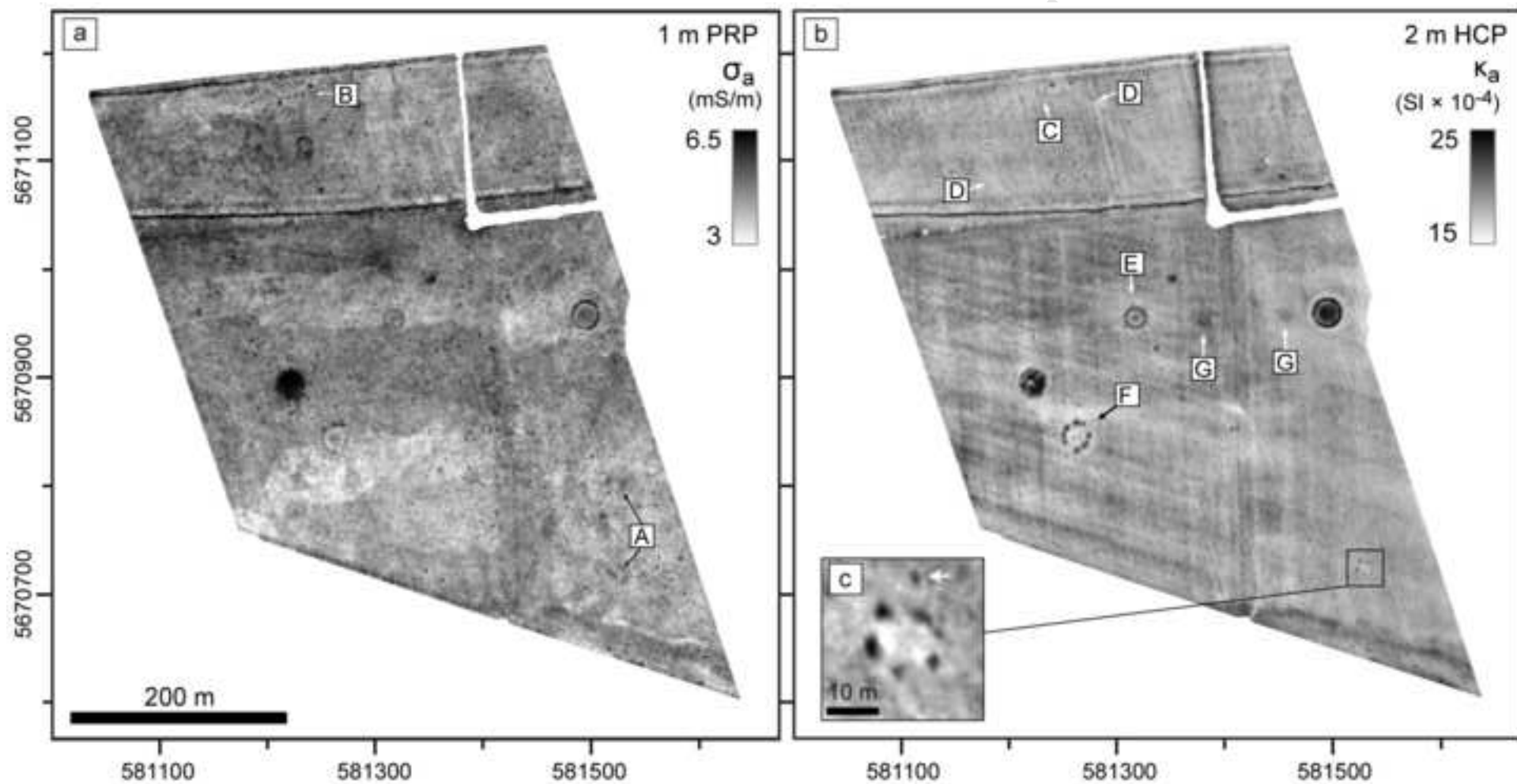


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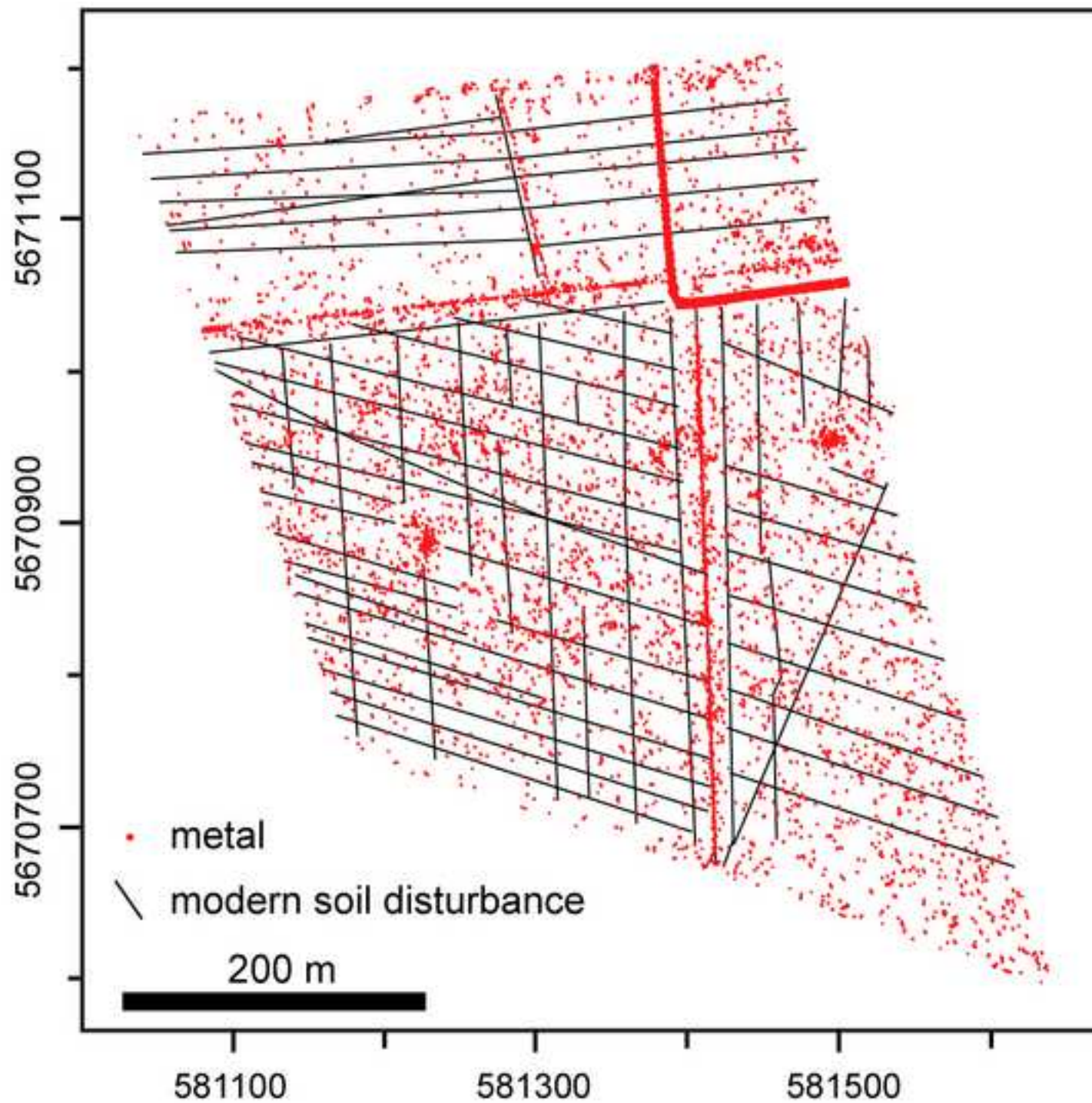


Figure 9

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