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Ground-penetrating Radar Survey over Bronze Age Circular Monuments on a Sandy Soil, Complemented with Electromagnetic Induction and Fluxgate Gradiometer Data

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ABSTRACT This paper presents a ground-penetrating radar (GPR) survey over two circular structures originally surrounding Bronze Age burial mounds at the site of Koekelare (western Belgium). The region is characterized by sandy soils. Their low water storage capacity and the consequent moisture contrasts in dry summers played an important role in the detection of over 1000 Bronze Age funeral monuments through aerial archaeology in the past few decades. At Koekelare, low attenuation of GPR waves resulted in the detection of a double and single circular ditch. A fluxgate gradiometer survey and electromagnetic induction (EMI) measurements did not clearly reveal the ditches. For the GPR wave velocity analysis, constant velocity migration tests were combined with time-domain reflectometry (TDR). The TDR measurements were made at different depths within the ditches and in the adjacent undisturbed soil, so that the differences in the physical soil parameters could be assessed.

At a depth of approximately 0.45 to 0.8 m, the relatively homogeneous ditch fill produces few GPR reflections compared with the undisturbed soil, and is visible as a weak negative anomaly on the horizontal slices. At this depth, the grey or brownish black ditch fill was found in augering samples, clearly distinguishable from the yellowish brown sandy soil outside the ditches. The transition between the ditch and the underlying soil caused a gradual reflection of radar energy at a depth of approximately 0.8 to 1.2 m, although TDR showed no marked differences in relative permittivity between the ditches and the surrounding soil, and no clear steps as a function of depth. Copyright © 2009 John Wiley & Sons, Ltd.

Key words: Ground-penetrating radar; Bronze Age funeral monuments; wave velocity analysis; time-domain reflectometry; augering; aerial archaeology

Introduction

In the past decades, ground-penetrating radar (GPR) has become a widely used instrument for the prospection of archaeological sites, providing high-resolution data in three dimensions. Its use is obvious where a high contrast in relative permittivity exists between archaeological features and surrounding soil (e.g. stone walls). Ground-penetrating radar surveys of structures constructed from perishable materials are less frequent (see e.g. Lück and Eisenreich, 1999;

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David *et al.*, 2004) as these are more difficult to detect, especially if they are of limited dimensions. Nevertheless, also in these cases, GPR can provide complementary information to other geophysical techniques and add depth information. In this article we present the results of a GPR prospection over the remains of two burial mounds in western Belgium, and compare them with an electromagnetic induction (EMI) and a fluxgate gradiometer survey.

Since the beginning of the 1980s, over 1000 Bronze Age burial mounds have been detected by aerial photography in the provinces of West- and East-Flanders, an area of ca. 6000 km^2 with mainly sandy soils (Figure 1a). Most examples date back to around 1800–1500 BC (Middle Bronze Age). They can be attributed to the so-called Hilversum culture (Ampe *et al.*, 1996) and are often found in clusters of up to 10 monuments. Circular ditches, which surrounded the mounds, are the only remnants of the monuments. The ditches have filled up but remain visible as crop marks. In contrast to eastern Belgium, where several monuments are still visible in the landscape, the mounds themselves have not been preserved due to erosion and intensive agricultural activity. Nevertheless, the often asymmetric filling of the ditches and the presence of badger's burrows are strong indications for their existence in the past. On some sites, augering has been carried out and approximately 25 sites have been excavated completely or partially. In some cases, cremated bone fragments and pottery, probably originating from urns, were found.

Although the aerial photograph database held at Ghent University contains a large number of detected burial sites, there are restrictions attached to aerial archaeology. The detection is time-, season- and crop-dependent and the rectification of oblique photographs is never perfect. Moreover, this method does not provide information on the depth of the archaeological features and the nature of the soil. Therefore, the aim of the present study was to investigate the potential of geophysical techniques as a complementary technique for the detection of circular monuments in the sandy region of Flanders, and for the estimation of their depth.

Site description

The study area is part of a Bronze Age cemetery of 500 by 225 m, one of the largest in the region, consisting of at least eight circular structures (Bourgeois *et al.*, 1998), including a double circle and a disc-shaped monument. It is situated in Koekelare-Boutikel, West-Flanders (Figure 1a), on the edge of the slightly undulating plateau of Aartrijke-Wijnendale. This plateau was formed by erosion-resistant material of Tertiary age, which can locally be found at less than 1 m depth. The topsoil consists of more than 80% sand, an aeolian deposit of Late Pleistocene age. During the survey, the site was used as an arable field. The site was discovered through aerial photography by pilot J. Semey in August 1990. Several structures belonging to the cemetery are visible as crop marks on Figure 1c and indicated on the map in Figure 1b. Because these crop marks mostly appear during extremely dry periods, the differences in crop vigour are likely to be caused by moisture stress. This explains why in Flanders crop marks are most often found on sandy soils, characterized by a fast drainage and a low moisture storage capacity. On the aerial photographs, some structures are not entirely visible since the area is divided into small parcels with different crops, as is often the case in Flanders. The double circle and one of the single circles were selected for the geophysical survey (Figure 1b). Adjacent to the single circle is a rectangular structure (Figure 1d), which may belong to the Iron Age or even the Roman period. The reuse of Bronze Age cemeteries in the Iron Age is known from excavations, and this dating would agree with the discovery of late Iron Age allotment structures during nearby rescue excavations.

Geophysical data acquisition and processing

Prospections were carried out in February 2008. To define the corner points of the grids, a Trimble AgGPS 332 differential geographical positioning system (GPS) was used. An area of 50 by 50 m over the double ditch was investigated. A magnetic prospection was performed with a

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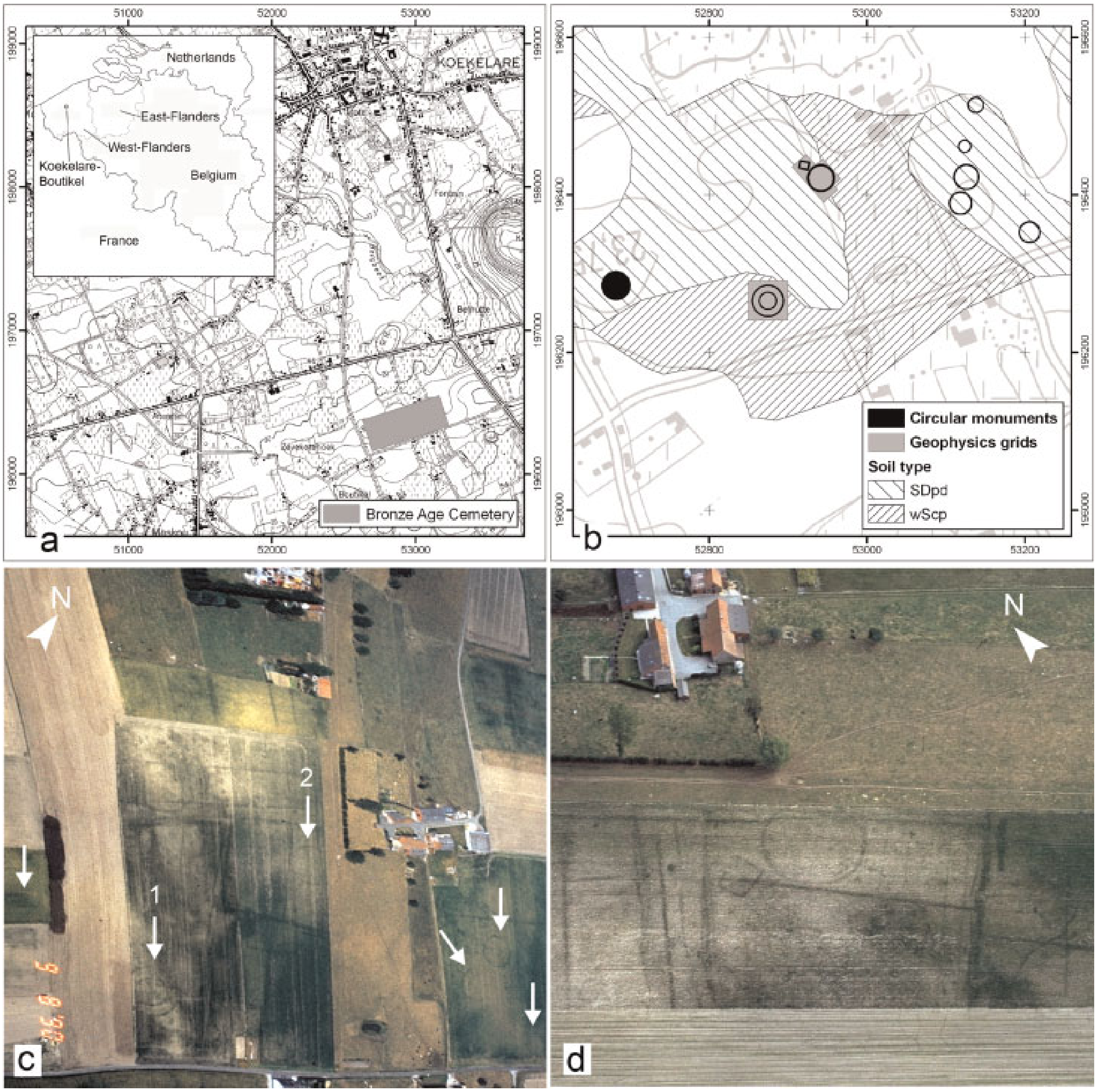

Figure 1. (a) Location of the site. (b) Location of the monuments within the cemetery, and the grids over the two circles selected for geophysical prospection. The soils can be described as 'moderately dry or moderately wet loamy sand without profile development and with presence of glauconite' (SDpd) and 'moderately dry loamy sand without profile development on a clay–sand substratum' (wScp) (Vlaamse Landmaatschappij, 2001). (c) Aerial photograph showing (1) the selected double circle and (2) the single circle, as well as several other monuments belonging to the site. (d) Aerial photograph of the single circle and a rectangular structure. This figure is available in colour online at www.interscience.wiley.com/journal/arp

Geoscan FM256 fluxgate gradiometer. Readings were taken at an inline distance of 25 cm and a cross-line distance of 50 cm. A zero mean traverse function, a periodic filter and a $\sin(x)/x$ interpolation were applied.

An EMI survey was conducted with a Geonics EM38DD ('dual dipole') sensor, consisting of two single EM38 instruments, attached in perpendicular arrangement. It enables measuring the horizontal coplanar (HCP) and vertical coplanar (VCP) coil orientations simultaneously. The quadrature-phase response, related to the apparent electrical conductivity (ECa), was measured in HCP orientation and the in-phase response, related to the apparent magnetic susceptibility (MSa), in VCP orientation (Simpson *et al.*,

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2009a,b). The sensor was pulled manually in a sled and positions were recorded with the differential GPS. The cross-line distance was 30 cm and the inline distance less than 10 cm. Processing involved correction of the time drift, noise filtering and interpolation with ordinary kriging.

Ground-penetrating radar measurements were taken over the double ditch and in an area of 36 by 60 m over the single ditch, with a hand-towed Sensors and Software pulseEKKO PRO and a 500 MHz antenna. Data were collected with an inline spacing of 5 cm, the cross-line distance was 25 cm and the sampling interval 0.2 ns. The direction of the lines was N–S for the double circle and NW–SE for the single circle. Processing included the application of a fixed gain and a band-pass filter with cut-off frequencies of 150 and 1000 MHz. No topographical corrections were made because the terrain is virtually flat.

Velocity analysis

For the GPR wave velocity determination, a range of constant velocities (in $0.0025\,\mathrm{m\,ns^{-1}}$ increments) was used as input for a frequency–wavenumber migration algorithm (Leckebusch, 2000). For the migration tests, the diffractions caused by the drainage system under the field were used, as few other hyperbolae were available; the ditches themselves only became visible in the depth-slices. The drains run at different depths not known exactly before the survey (from about 0.65 m to 1.1 m; see the slices in Figure 2a, b, c and d) and consist of brick pipes with a diameter of approximately 10 cm. Only the drains running more or less perpendicularly to the survey lines were used for the migration tests (Figure 2e and f).

For the double ditch, the GPR wave velocity obtained from the migrations tests on the drainpipes lay around $0.0683\,\mathrm{m\,ns^{-1}}$. The deepest drain (Figure 2e, D1) yielded the highest velocity ($0.0694 \pm 0.0026\,\mathrm{m\,ns^{-1}}$), whereas the lowest value was recorded for the immediately adjacent drain D2 (0.0665 ± 0.0026 m/ns). For the single circle, surveyed three weeks before the double ditch, clear hyperbolae were only present at a depth of around 0.70 m (Figure 2c and f). The resulting velocity was $0.0794 \pm 0.0042\,\mathrm{m\,ns^{-1}}$.

Additionally, time-domain reflectometry (TDR) measurements were carried out with a Campbell Scientific TDR100 instrument, in order to define the physical soil parameters and the velocity over the entire depth of the double ditch. The principles behind TDR are similar to GPR (Dalton and Van Genuchten, 1986; Campbell Scientific, 2007). A high-frequency electromagnetic pulse is generated and sent to the connecting coaxial cable and probe. The probe consists of metal rods forming two or three parallel waveguides, mounted in a handle made of hardened epoxy resin or a similar material. In this case the probe was made up of three rods each 23 cm long. The transition from the cable to the probe causes a change in the reflection coefficient because the impedance of the cable and the probe are normally not the same. The probe end is equally identified by a change in reflection coefficient. When the probe is inserted into the soil, the travel time of the pulse along the rods, which is dependent on the relative permittivity of the surrounding soil, is measured and the propagation velocity can be derived. Additionally, TDR can be used to measure the electrical conductivity by analysing the attenuation of the reflected signal and its effect on the slope of the TDR waveform.

Although in stony ground it can be difficult to insert the rods, the sandy soil at the site investigated, which was completely devoid of obstacles, posed no problems. Six series of TDR measurements were taken at different depths in the northwestern and southeastern corner of the grid, each time through the ditch and at distances of approximately 3 m from the ditch (Figure 2e, T1–T6). The middle of the ditch was verified with a gouge auger using the information from the sensor maps. The probe was inserted in the soil at depths of 0 to 1.2 m, with intervals of 0.2 m. In order to insert the probe at depths below 0.2 m, a borehole was drilled with a 6 cm wide Riverside auger until the required depth. The borehole was finished using a 6 cm wide sizing auger, producing a hole of uniform geometry with a flat bottom after the debris had been cleaned from the bottom of the hole. The probe was then pushed into the borehole using a

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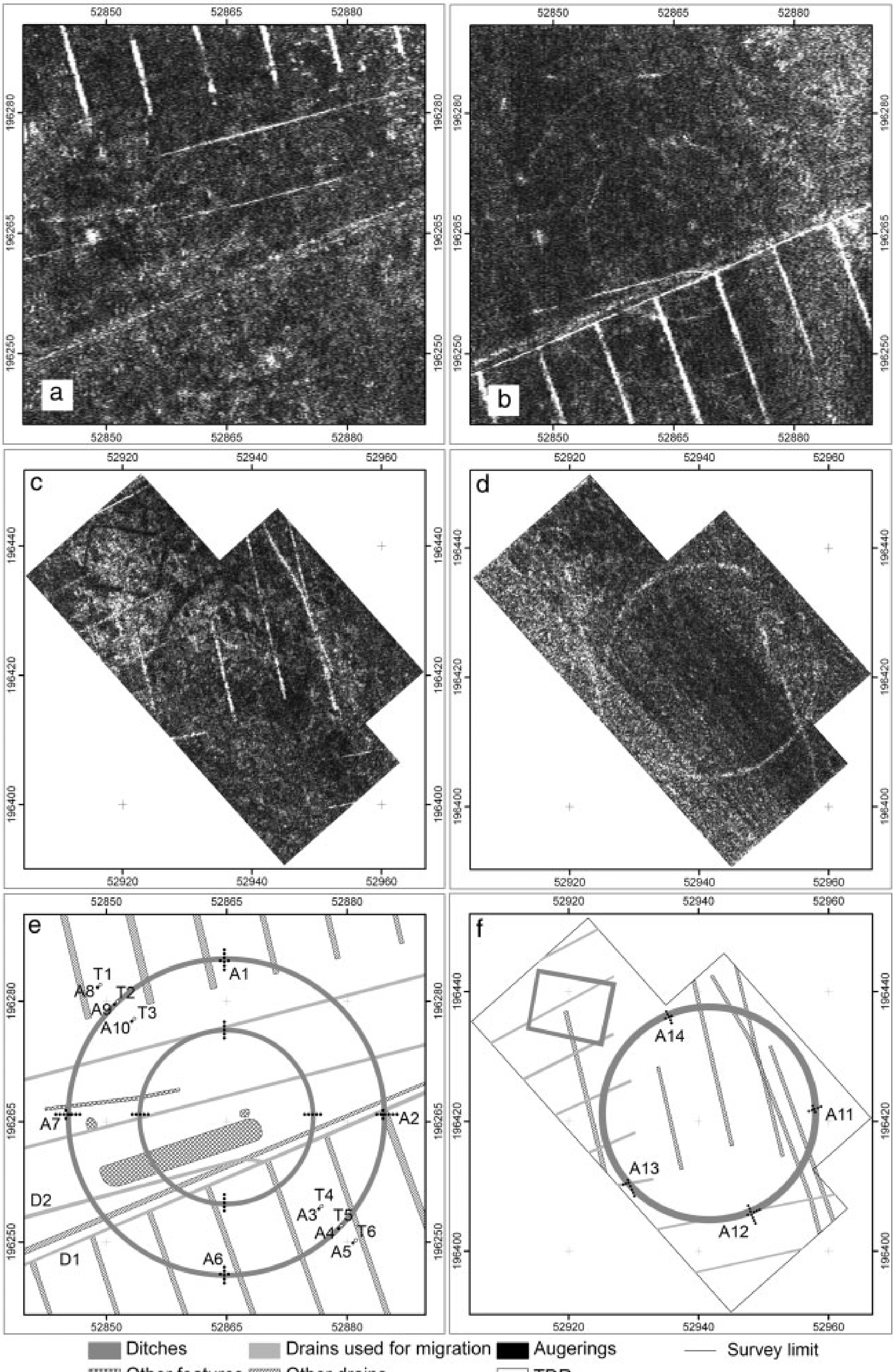

Figure 2. Ground-penetrating radar depth-slices (white = high reflection strength): (a) double ditch (0.66–0.70 m), (b) double ditch (0.96–1 m), (c) single ditch (0.71–0.75 m), (d) single ditch (1.11–1.15 m). Interpretation of the GPR results for (e) the double and (f) the single structures, with indication of the drains used for the migration tests and the TDR measurements (T1–T6) and auger positions (A1–A14) discussed in the text.

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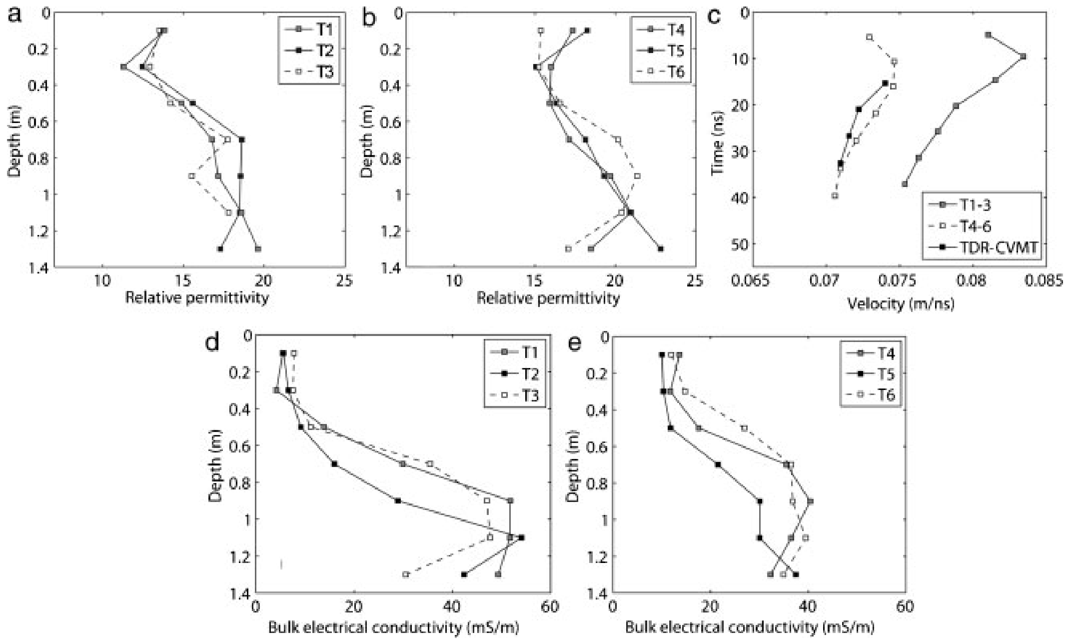

Figure 3. Results of the TDR measurements through the outer ditch of the double circular structure (T2 and T5) and at a distance of 3 m from that ditch (T1, T3, T4 and T6): two velocity curves in (c) were derived from the relative permittivity values of (a) TDR samples T1–T3 and (b) TDR samples T4–T6. The final velocity model used for the GPR time-to-depth conversion of the double ditch area was based on TDR and constant velocity migration tests (CVMT). Electrical conductivity measurements with TDR (d and e) showed a lower value for the ditch fill. For the location of the measurements, see Figure 2e, T1–T6.

1.5 m long PVC tube with an outer diameter of 6 cm, fixed to the probe handle. This ensured perfect vertical insertion of the probes into the soil. Since the results are affected by a soil volume with height 23 cm surrounding the rods, the theoretical measurement depths were 0.1 to 1.3 m (Figure 3).

As the root-mean-square velocity value was available from the migration tests, derived from drains at depths of approximately 0.65 to 1.1 m, the interval velocities given by the TDR were also converted to root-mean-square velocities. This yielded somewhat higher velocity values than obtained from the migration tests, especially in the northwestern corner (Figure 3c, T1–T3). The migration tests, performed on drains buried in trenches, may hence not be perfectly representative for the whole survey area. For the time-to-depth conversion of the GPR data from the double ditch, the velocity function shown in Figure 3c was utilized, based on the migration tests and the TDR measurements. For the single circle, only the velocity obtained from the migration tests was used (see above).

Results and interpretation

Figure 4a and b shows the results of the EMI survey over the double ditch. Some of the drainpipes are vaguely visible (A). A strong anomaly (B) is likely to be caused by a shallow metal object, probably a piece of wire. It is also visible in the GPR data (Figure 2a and b). However, the magnetic contrast with the surrounding soil was too small to reveal the circular structures themselves through the MSa survey. Nor did the fluxgate gradiometer data show the ditches. On the ECa map (Figure 4b) they are faintly visible in the southeast.

On the GPR depth-slices (Figure 2a–d), the most striking features are the drains. The traces of the circular ditches are much more subtle. From approximately 0.45 to 0.8 m below the surface, both the double and single structure are visible as a very weak negative anomaly, i.e. lower reflections (Figure 2a and c). Only the rectangular structure near the single circle is clearly revealed at this depth. From excavations at other sites it is known that the fill of the ditches often consists of

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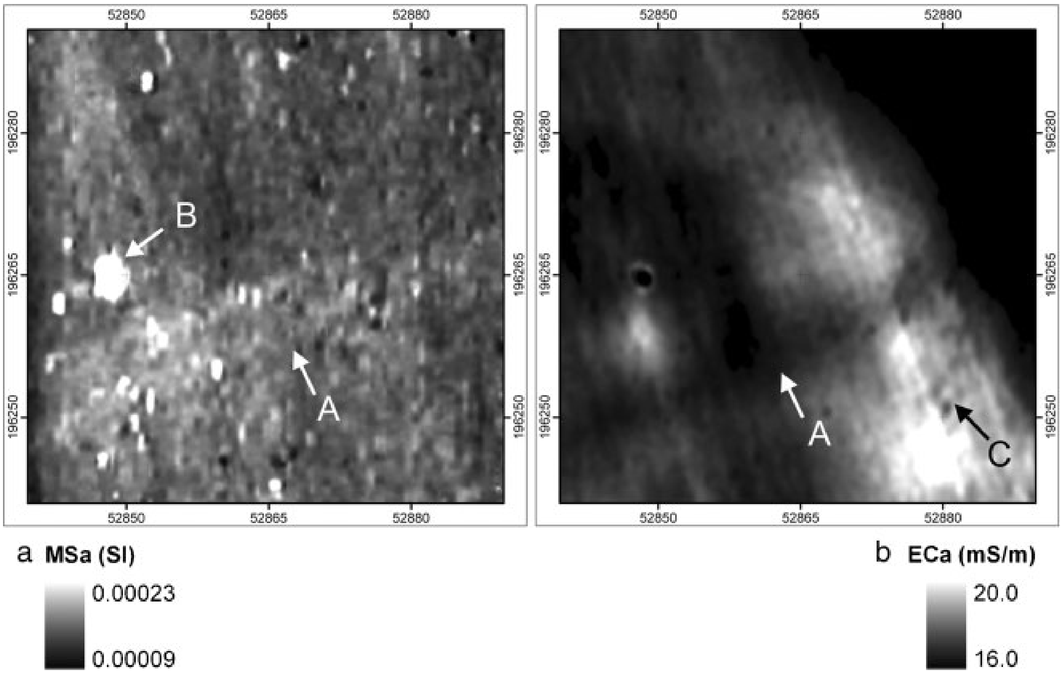

Figure 4. The EM38DD survey results over the double ditch. (a) MSa in VCP orientation. (b) ECa in HCP orientation. Drains are marked A, an anomaly probably caused by a piece of steel wire is shown as B and the ditch as C.

three layers (Ampe *et al*., 1996). At the base is a small humus-enriched layer, which accumulated when the ditch was still in use. On top of this, yellow sandy material can be observed, originating from the mound and suggesting fast filling of the ditch when it was no longer in use. After a stabilization phase, the upper filling consists of a dark layer, rich in humus (Figure 5).

The ditch fill can be assumed to be more homogeneous than the surrounding soil, which shows stronger reflections. Small differences in the relative permittivity, which in soils with low electrical conductivity controls the reflection coefficient, may for example originate in the transition between the plough layer and underlying undisturbed soil. Additionally, rust marks (gleying) may play a role. Gleying occurs in those parts of the soil that are alternately waterlogged (because of a high water table in winter) and dry (in summer). Horizons in stagnant water become depleted of iron because of its reduction from Fe^{3+} to Fe^{2+} and its solution (White, 1997; Ashman and Puri, 2002). The iron can become re-oxidized in better aerated zones such as plant roots and pores. It then forms orange-red or brown concentrations (Figure 5). Gleying is primarily caused by the combined presence of anaerobic microbes and organic matter, and hence is often found near perishable archaeological features such as ditches. At Koekelare, gleying starts at a depth of about 0.6 m (Van Ranst and Sys, 2000), and was observed during the augering as rusty coloured earth, for example around the eastern part of the double ditch. It has been shown that iron oxides can be a cause of GPR reflections in sandy soils (Van Dam *et al*.,

Figure 5. Section through a ditch at the site of Kortemark-Koutermolenstraat near Koekelare, showing orange-brown concentrations due to the re-oxidation of iron.This figure is available in colour online at www.interscience.wiley.com/journal/arp

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2002). The iron oxides do not directly affect any of the three components defining the impedance (dielectric permittivity, electrical conductivity, magnetic permeability). Instead, the larger moisture retention capacity of the iron oxides influences the volumetric water content and the relative permittivity. At Koekelare, these processes are subtle and locally varying, as in the TDR measurements no sharp transitions in the relative permittivity were recorded with depth, and no large permittivity differences between the ditch and the surrounding soil can be observed (Figure 3a and b).

Only the inner circle of the double ditch does not show as a negative mark (Figure 2a). This might be explained by the fact that the inner circle existed only for a short period. Indeed, according to excavation results from other sites, there are two types of double monuments: those where both ditches were in use for a long period, and those where the inner ditch was filled soon after it had been dug. In the latter case, the fill consists of material with low humus content similar to the original soil, which is less easily detected by aerial photography or geophysical prospection and at Koekelare was not even recognized during the augering. These temporary ditches probably result from the ritual demarcation of the central grave area and were covered after the funeral, during the construction of the mound and the digging of the outer ditch (e.g. at Ursel-Rozestraat; Bourgeois *et al.*, 1989). In other cases (e.g. at Waardamme; Demeyere and Bourgeois, 2005), there are indications that the first ditch was dug around a small barrow and filled up when a larger barrow was built, which was also surrounded by a ditch.

Radiocarbon dates have shown that this twofold classification might also be of chronological relevance: the monuments with a temporary inner ditch seem to be the oldest, dating back to between the twenty-second and eighteenth century BC, i.e. the transition between the final stage of the Late Neolithic and the Early Bronze Age. Nevertheless, so far this chronology rests on only a few well-dated examples. Moreover, assigning a detailed chronology to the geophysical results at Koekelare remains tentative without excavations.

At a depth of approximately 0.8 to 1.15 m (0.85 to 1.25 m for the single ditch), both monuments show a reflection of radar energy (Figure 2b and d). To further interpret and test the depths estimated by means of the GPR and TDR data,

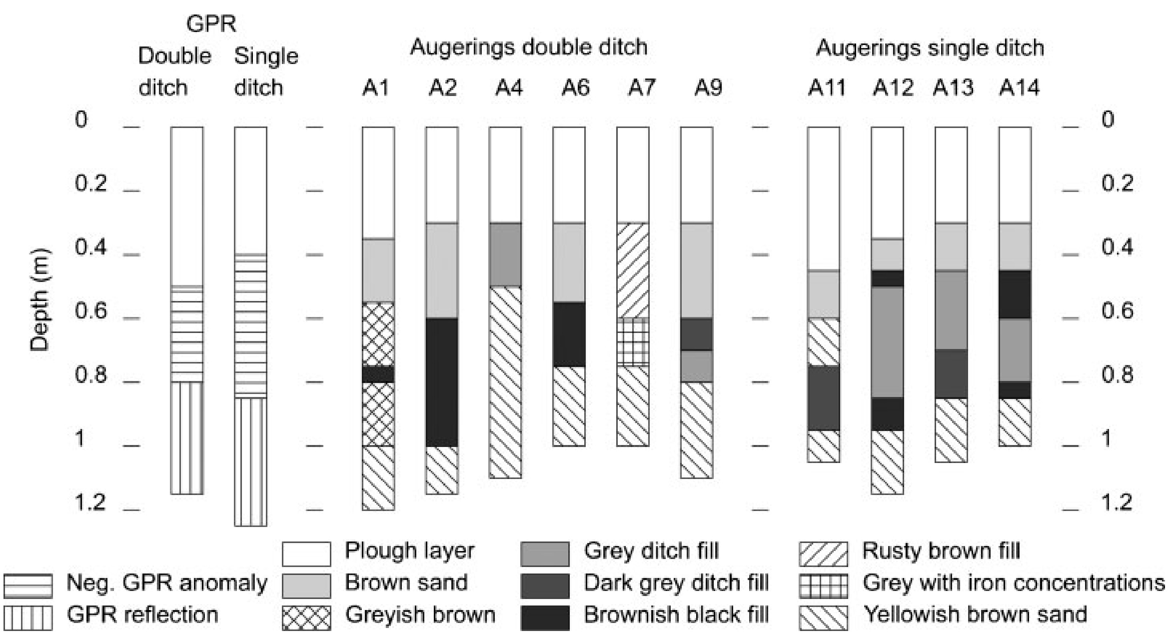

Figure 6. Comparison of the depth estimation based on migration and TDR, and the augering results. Except for A4 and A9 (gouge auger), all augering was performed with an Edelman auger. For the auger positions, see Figure 2e and f, A1–A14. From each series of augering, the sample originating from the deepest part of the ditch was selected.

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these were compared with a set of augering records over the double and single ditch (Figure 2e and f, A1–A14), carried out with a half-cylindrical gouge auger of 2 cm diameter and an Edelman auger of 5 cm diameter. On average, in the core samples the grey or brownish black ditch fill does not reach a depth greater than 0.8 m (outer ditch of the double structure) or 0.9 m (single ditch), as is shown in Figure 6. As a consequence, it seems reasonable to assume that, whereas the negative GPR anomaly corresponds to the actual ditch fill, the reflection represents the transition between the ditch and the underlying soil. Overall, clay content is low (on average below 8%), as was demonstrated by soil texture analyses on samples from augerings A3–A5 and A8–A10 (Figure 2e) with the hydrometer method (Gee and Bauder, 1986). Moreover, both EM38DD data (Figure 4b) and TDR measurements (Figure 3d and e) show lower electrical conductivity values for the ditch than for the immediate surroundings. The GPR signal is hence attenuated to a limited degree when passing through the ditch and is then gradually reflected by the underlying soil. Again the iron content of the underlying sand may play a role in the enhanced reflection of the GPR energy, although few rust marks were recorded in the auger results at this depth.

Conclusion

For 30 years, aerial archaeology has provided good results in the prospection of Bronze Age circular ditches on the sandy soils of the western part of Belgium. In this study, the potential of geophysical techniques for the detection of these funeral structures was assessed. The low clay content and correspondingly low attenuation allowed the detection of a concentric and a single monument by GPR. By contrast, fluxgate gradiometer and electromagnetic induction measurements were unsuccessful in revealing the ditches. On the GPR depth-slices, the homogeneous ditch fill is characterized by a relative absence of reflections. Given their fragmented character, the reflections in the surrounding soil may have been enhanced by the local presence of iron oxides, which indirectly affect the relative permittivity.

The inner ditch of the double concentric structure is not visible as a negative GPR anomaly. This may be due to the fact that it was not subject to slow sedimentation but filled very fast, with material similar to the surrounding soil. Such temporary ditches may have acted as ritual demarcations or surrounded a provisional barrow, later covered by a larger mound. Monuments with a temporary inner ditch have been shown to be older than those with two contemporary ditches, but more investigation is needed to confirm this and to place the different construction phases of the mounds chronologically.

At a deeper level, the transition between the ditch und the underlying soil shows a reflection, although TDR measurements showed no marked differences in relative permittivity between the ditch and the soil underneath the ditch. At Koekelare, TDR proved a useful complementary technique for determining the velocity of the GPR waves as few hyperbolae were available for constant velocity migration tests.

Circular ditches are not the only features to be expected on Bronze Age funeral sites. In a recent excavation of a complete cemetery (Cherretté and Bourgeois, 2005), two post circles were unearthed, which had not been identified through aerial photography. Future geophysical prospecting combined with subsequent excavations may inform us as to whether these smaller features are within the detection limit of GPR.

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